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Summary Engineering Report for Abyssal Plains Waste Isolation Project

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The Department of Defense's Naval Research Laboratory (NRL) has been tasked by the Strategic Environmental Research and Development Program (SERDP) to assess the environmental viability of the isolation of dredged material, sewage sludge, and municipal incinerator fly ash on the abyssal plains of the deep ocean. Abyssal Plains Waste Isolation (APWI) is the term given by this project to the isolation of waste on the abyssal plains. Oceaneering Technologies (OTECH) has been tasked by NRL to assess waste handling technologies regarding engineering feasibility and reliability.

The first step in assessing the engineering feasibility and reliability of waste handling technologies was to identify top level or system level requirements that will have to be met by any APWI concept considered. Sources of APWI system level requirements were environmental regulations, physical and chemical characteristics of the waste streams (dredged material, sewage sludge, and municipal incinerator fly ash), weather/site conditions, and standard references for ocean going vessels. A literature search of each of these sources was performed. The information extracted from these various sources was placed into the categories of handling, transportation, and emplacement. Systerr l~el requirements were then derived from this information

The second step was the technical assessment of candidate waste handling technologies which was a three part process. First, through a series of patent research, brainstorming new ideas, and a methodical down-select and evaluation exercise, five concepts were chosen to be evaluated. Technical issues of these five concepts were then

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identified and explored as the second major process step. Lastly, a risk assessment of these concepts was performed to determine overall technical and operational feasibility. The five system concepts assessed were: Surface Emplacement, Remotely Operated Vehicle (ROV) Glider, Direct Descent Disk, Pipe Riser, and Tethered Container. To eliminate repetition, elements common to all system concepts, such as transporter systems, containers, handling systems, and waste specific gravity were researched separately.

The third step, economic viability, estimated both the capital costs and the annual operating costs of technically viable APWI concepts. By estimating these costs, APWI concepts can be compared to existing isolation methods to examine the viability of APWI. In addition, comparisons may be made between the APWI concepts to determine the most cost effective concept.

The work reported herein is part of the project "Technical and Economic Assessment of Storage of Industrial Waste on Abyssal Plains" managed by the Naval Research Laboratory and sponsored by the Strategic Environmental Research and Development Program.

ABSTRACT

The Department of Defense's Naval Research Laboratory (NRL) has been tasked by the Strategic Environmental Research and Development Program (SERDP) to assess the environmental viability of the isolation of dredged material, sewage sludge, and municipal incinerator fly ash on the abyssal plains of the deep ocean. Abyssal Plains Waste Isolation (APWI) is the term given by this project to the isolation of waste on the abyssal plains. Oceaneering Technologies (OTECH) has been tasked by NRL to assess waste handling technologies regarding engineering feasibility and reliability.

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The second step was the technical assessment of candidate waste handling technologies which was a three part process. First, through a series of patent research, brainstorming new ideas, and a methodical down-select and evaluation exercise, five concepts were chosen to be evaluated. Technical issues of these five concepts were then identified and explored as the second major process step. Lastly, a risk assessment of these concepts was performed to determine overall technical and operational feasibility. The five system concepts assessed were: Surface Emplacement, Remotely Operated Vehicle (ROV) Glider, Direct Descent Disk, Pipe Riser, and Tethered Container. To eliminate repetition, elements common to all system concepts, such as transporter systems, containers, handling systems, and waste specific gravity were researched separately.

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PREFACE

This report summarizes the engineering assessment of Abyssal Plains Waste Isolation (APWI) of dredged material, sewage sludge, and municipal incinerator fly ash. This study effort consisted of the following three project phases: system requirements definition, technical analysis, and cost estimation. Each of these phases concluded with a separate report that will be referenced throughout this summary report. These separate reports are:

Title	Report #
System Requirements Report for Abyssal Plains Waste Isolation Project	APWI 94-01
Technical Assessment Report for Abyssal Plains Waste Isolation Project	APWI 94-02
Economic Viability Report for Abyssal Plains Waste Isolation Project	APWI 94-03

The System Requirements Report presented the system level requirements for candidate waste handling technologies regarding Abyssal Plains Waste Isolation (APWI) of dredged materials, sewage sludge, and municipal incinerator fly ash. In the development of these system level requirements, Oceaneering Technologies (OTECH) examined existing environmental regulations, physical and chemical properties of the waste streams, weather and site conditions, and existing regulatory constraints on vessels. These sources were chosen because they cover all major areas that may place design constraints on whichever technology is chosen and give broad based system level requirements to use in the evaluation of candidate technologies.

The Technical Assessment Report summarized the results of an engineering study effort to develop and analyze the technical feasibility of conceptual approaches to APWI. Existing patents (U.S. and foreign) related to deep ocean isolation of various materials were examined as the baseline for previous work. By combining common approaches, concepts in 128 patents were reduced to 30 concepts for evaluation. These 30 were then evaluated against high level technical, environmental, and cost criteria to determine their relative merit. Five of these concepts were selected for further definition and evaluation.

The Economic Viability Report estimated the capital and annual costs of concepts identified in the Technical Assessment Report as technologically feasible. The results of this costing exercise may be used to assess the viability of APWI by comparing the concepts' emplacement costs to existing isolation methods. In addition, the results may be used to compare costs between APWI concepts, to identify optimal concept(s), or to identify concept(s) that are not economically viable.

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1.0 SUMMARY

The Naval Research Laboratory (NRL) has been tasked by the Strategic Environmental Research and Development Program (SERDP) to assess the environmental viability of isolating dredged materials, sewage sludge, and municipal incinerator fly ash on the abyssal plains of the deep ocean floor. Oceaneering Technology's (OTECH's) role in this study is to assess candidate waste handling technologies regarding engineering feasibility and reliability.

This report summarizes OTECH's study effort which consisted of three interrelated phases: systems requirements definition, technical assessment of concepts, and economic assessment of concepts. An overview of these three phases are contained in Sections 3.0, 4.0, and 5.0 of this report.

In the system requirements phase, information was gathered to quantify the design parameters that any potential Abyssal Plains Waste Isolation (APWI) concept must meet. Requirements were derived from:

- Environmental regulations
- Waste stream physical and chemical properties
- Environmental conditions encountered from port to site
- Site characteristics
- General regulatory design constraints for vessels

The technical assessment phase of the project included a review of concepts in 128 patents relevant to APWI, a down-selection process which narrowed the concepts to five, a concept definition task to detail each concept, and a reliability analysis to compare the technical and operational risks between concepts.

The five concepts that were analyzed are:

- Surface Emplacement - A customized barge is designed with 51 separate cells, which are lined with disposable, high strength, high density, flexible fabric bags. The waste material is loaded into the individual bags, which are closed before leaving port. The vessel then transits to the APWI site, opens the trap doors to the cells to release the bags, which free-fall to the seafloor. The bag isolates the material from the intervening water column during descent. After impact with the bottom, the waste material remains contained in the bag. Experiments conducted by the U.S. Army Corps of Engineers has demonstrated that these types of bags do not burst upon impact with the seafloor.

- ROV Glider - A submersible vessel (ROV Glider) is used to transport waste material to the abyssal isolation site, submerge, release the waste at a specified altitude above the seafloor, and return back to the ocean surface for recovery. Similar to Surface Emplacement, the Glider contains individual compartments lined with flexible bags. The Glider is negatively buoyant when loaded with waste, so it is towed to the APWI site in a floating "garage". At the site, the ROV Glider is released from its "garage" and descends in an actively controlled, spiral-shaped flight path until it nears the sea floor. Then its trap doors open, the containerized load falls out, and the now positively buoyant Glider returns to the surface. The ROV Glider is then recovered by the surface ship into its "garage." The ROV Glider is autonomously controlled, but can be minimally controlled from the surface as a backup mode.

- Direct Descent Disk - A vessel in the shape of a shallow disk with a large diameter delivers its cargo to a predetermined altitude off the seafloor and then releases it. The disk also has numerous

cargo cells lined with bags. It is negatively buoyant when loaded with waste. It is transported to the site in a "floater module" and when released, descends in a near-vertical path to near the sea floor, brakes, releases its containerized load via trap doors, becomes positively buoyant, and ascends to the surface. In contrast to the ROV Glider, the Direct Descent Disk does not follow a closed-loop controlled glidepath. Its inherently stable hydrodynamic design allows it to perform the operation without active stabilization.

- Pipe Riser - A set of four large diameter pipes run vertically from the ocean's surface to near the seafloor to transport waste to the abyssal isolation site. A transport ship hauls the waste material in bulk from the port to the APWI site, where it is pumped to the riser for dilution with cold water prior to disposal. Two pipes bring cold water from 700 m depths to slurryize and thermally equalize the waste with abyssal seafloor temperature. The slurryized waste travels down the other two pipes, isolating the waste from the water column. The waste material is discharged near the bottom to form a mound on the seafloor. The pipe riser is dynamically positioned at the top and moored at the bottom to maintain station.

- Tethered Container - A ship is loaded with bulk waste at port and transits to the APWI site. A large on-board rigid container is then loaded with bulk waste and winched from the ship to near the seafloor. At this point, the bottom of the container is opened and waste falls out to form a mound on the seafloor. The container is winched back to the surface platform to be refilled and the cycle continued.

These five concepts were then compared to the system level requirements documented in the System Requirements Report. The Tethered Container concept was disqualified at this point because a handling system capable of emplacing the required amount of waste per system per year was not technically feasible. All system level requirements can be met by the remaining four concepts.

Two independent reliability analyses, Fault Tree Analysis (FTA) and Failure Modes Effects and Criticality Analysis (FMECA) were performed on the remaining four APWI concepts. The results of these analyses provided a ranking of the four systems according to combined technical and operational risk. In increasing order of risk, they are:

- Surface Emplacement
- Direct Descent Disk
- ROV Glider
- Pipe Riser

Of the failure modes identified, all can be overcome by adding redundancy in the design. Areas requiring additional study, modeling and/or testing were identified for each concept as a result of the reliability analyses. These are critical areas which require close control during development.

Lastly, estimated were prepared to determine the nonrecurring capital costs and the recurring annual costs of these four remaining concepts.

- Surface Emplacement - Concept annual cost is $15 million. Cost of emplacement of dredged material is $12/yd^3$, and of sewage sludge and fly ash is $15/metric ton.

- ROV Glider - Concept annual cost is $25 million. Cost of emplacement of dredged material is $16/yd^3$, and of sewage sludge and fly ash is $20/metric ton.

- Direct Descent Disk - Concept annual cost is \$32 million. Cost of emplacement of dredged material is \$20/yd^3, and of sewage sludge and fly ash is \$24/metric ton.

- Pipe Riser - Total annual cost is \$11 million. Cost of emplacement of dredged material is \$15/ yd^3, and of sewage sludge and fly ash is \$18/metric ton.

From a technical perspective, taking cost into consideration, the following conclusions are reached.

- Surface Emplacement offers the least complex, most reliable system for large scale, long term deep ocean isolation of waste. The drawbacks to this concept are the probable scattering pattern of the bags during emplacement and the potential for ripping of waste-filled bags by metal edges in the barge loading and releasing processes. It is expected that early demonstrations to assess environmental impact will necessitate that bags be grouped into piles to simulate long term emplacement operations. Therefore, this concept appears to be most viable for full scale operation, but not conducive for near term demonstration and environmental experimentation.

- For near term demonstrations and experiments, as discussed above, the Direct Descent Disk appears to be the most practical approach for emplacement of waste in clusters. It requires the least amount of active control of the remaining concepts and can be easily modeled and scale tested for a quick development and validation program. It also can be configured for surface release. This feature is beneficial for large scale surface experiments. It could be used in a production mode to emplace highly contaminated waste near the seafloor.

2.0 INTRODUCTION

The Strategic Environmental Research and Development Program (SERDP) tasked the Naval Research Laboratory (NRL) to assess advantages, disadvantages, and environmental viability of storing dredged materials, sewage sludge, and municipal incinerator fly ash on the abyssal plains of the ocean. This study is called the Abyssal Plains Waste Isolation (APWI) Project. NRL has six objectives in assessing the storage of waste on the abyssal plains.

1. Identify environmental characteristics of abyssal plains which affect suitability for waste isolation;
2. Select abyssal plain areas offering most promise of achieving waste isolation;
3. Assess candidate waste handling technologies as to engineering feasibility and reliability;
4. Develop a survey plan to obtain a baseline of the physical, chemical, biological, and geological characteristics of a suitable area;
5. Prepare a monitoring program plan; and
6. Conduct an economic analysis of the deep ocean isolation concepts.

Oceaneering Technologies (OTECH) was tasked by NRL to assess waste handling technologies as to engineering feasibility and reliability, which is objective number three above. OTECH has further divided this objective into three tasks:

1. System Requirements
2. Technical Assessment
3. Economic Viability

Figure 2.0-1 illustrates OTECH's system engineering approach to this project. As shown, each of the three major tasks ended in a stand-alone report as follows:

Title	Report #
System Requirements Report for Abyssal Plains Waste Isolation Project	APWI 94-01
Technical Assessment Report for Abyssal Plains Waste Isolation Project	APWI 94-02
Economic Viability Report for Abyssal Plains Waste Isolation Project	APWI 94-03

The purpose of the System Requirements Report is to find and document applicable assumptions and requirements used to evaluate potential concepts. Since system level requirements must be met by all potential concepts, these requirements will be used to drive the detailed concept design. System level requirements, with regard to APWI, are constraints placed upon a system by environmental regulations, physical/chemical

properties of waste being handled, volumes of waste, environmental conditions encountered from port to site, site characteristics, and general regulatory design constraints for vessels.

The Technical Assessment Report deals with the down-selection, synthesis, concept definition, and reliability assessment of concepts.

The Economic Viability Report analyses the capital and annual operating costs for the four most viable APWI concepts. It also estimates the emplacement cost/ton for sewage sludge and municipal incinerator fly ash and the cost/yd^3 for contaminated dredged material. In addition, the development costs of each concept is estimated.

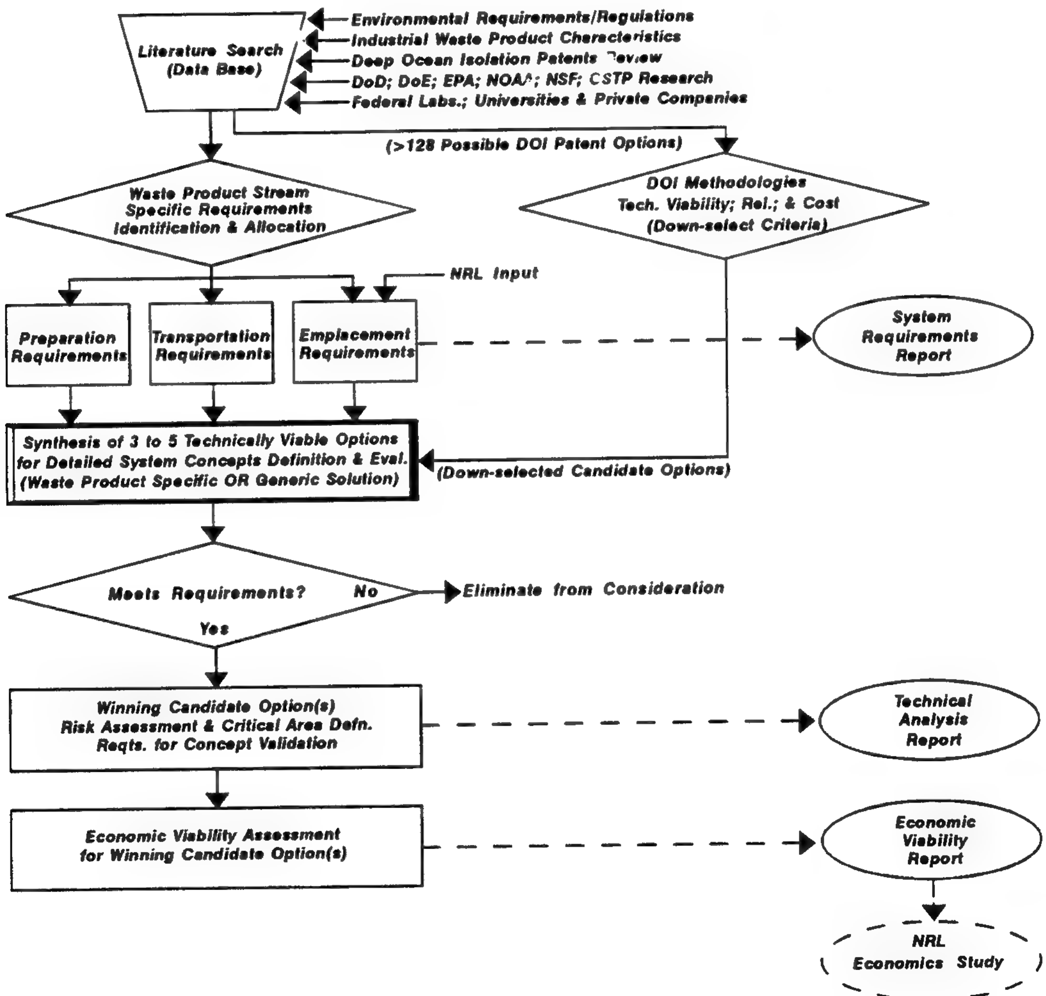

Figure 2.0-1 APWI Systems Engineering Approach

3.0 SYSTEM REQUIREMENTS OVERVIEW

As the first step of assessing waste handling technologies, OTECH identified top level or system level requirements that will have to be met by any candidate technology considered. System level requirements were derived from:

- Environmental regulations
- Waste stream physical and chemical properties
- Environmental conditions encountered from port to site
- Site characteristics
- General regulatory design constraints for vessels

These sources were chosen because they cover all major areas that may place design constraints on any systems solution and/or applicable technologies.

Applicable environmental regulations were converted to a logical flow diagram (found in Appendix B of the System Requirements Report) to illustrate the relationship between regulations and to create a road map of all relevant decision steps applicable to both hazardous and nonhazardous waste handling and disposal. This flow diagram facilitated the identification of essential steps necessary in a viable Abyssal Plains Waste Isolation methodology. It was also used as the foundation for all derived environmental regulatory system level requirements regarding handling, transportation, and oceanic emplacement. These regulatory system level requirements must be met either by designing to these standards or assuming that certain laws will be modified. System level requirements derived from environmental regulations are significantly larger in number than all other categories of system level requirements combined.

Oceaneering Technologies independently researched database sources of waste stream properties and correlated our findings and waste stream parameter values with those found by NRL. These results from the two independent investigations were combined to establish a best estimate for waste stream values. Physical and chemical properties of the waste streams led to general system level requirements with respect to handling, transport and emplacement of these wastes.

Oceaneering Technologies utilized the CD ROM version of the "Atlas of the World" to research sea state and wind magnitudes at the candidate Abyssal Plain Waste Isolation sites to assess the potential operational availability versus the system design capabilities. In addition, based on a previous study utilizing a large in-house data base, OTECH established worst case current versus depth values. Correlation to Abyssal Plains Waste Isolation proposed sites indicates satisfactory design margins of safety. Weather requirements and environmental conditions expected at five potential emplacement sites led to system level requirements that maximize the average number of operating days and survivability if unexpected conditions arise. Current velocities expected at these sites led to system level requirements with respect to emplacement accuracy. Temperature, abyssal depth pressure and distance from port to site also led to design requirements.

Existing standard regulations for oceangoing vessels led to straightforward regulatory design constraints regarding different vessel types.

OTECH believes that with the research done to date, all significant system level requirements have been identified. These system level requirements were then applied to candidate waste handling technologies to assess their viability and to select the optimal waste handling approach.

3.1 ENVIRONMENTAL REQUIREMENTS

The following list of documents were reviewed to extract pertinent environmental regulations:

- 40 CFR Protection of the Environment
- 49 CFR Transportation
- 46 CFR Shipping
- 29 CFR Labor
- 33 CFR Navigation and Navigable Waters
- Marine Protection, Research and Sanctuaries Act (MPRSA)
- Resource Conservation and Recovery Act (RCRA)
- Clean Water Act
- 58 FR 9248 Standards for the Use and Disposal of Sewage Sludge
- MIL-HDBK-1005/8 Domestic Wastewater Control
- Technical Notes from US Army Corps of Engineers Environmental Effects of Dredging

For the purpose of research on this project it is assumed that the 1988 Ocean Dumping Ban Act Amendment of MPRSA would be amended to accommodate deep ocean isolation of sewage sludge.

Regulatory information pertaining to handling, transportation, and oceanic emplacement were extracted from these documents. The extractions from different regulations were grouped into categories of handling, transport, and emplacement and placed in procedural order. This began with 40 CFR and followed the flow of logic, tracing cross references, until the regulations told the entire story and gaps between information closed. A simplified flow diagram, Figure 3.1-1, was created to show the general flow of these regulations. Each block of the simplified diagram was broken down in much greater detail and is included as Appendix B in the System Requirements Report. Table 3.1-1 lists the environmental regulations and gives section numbers that contain applicable information pertinent to handling, transportation, and oceanic emplacement.

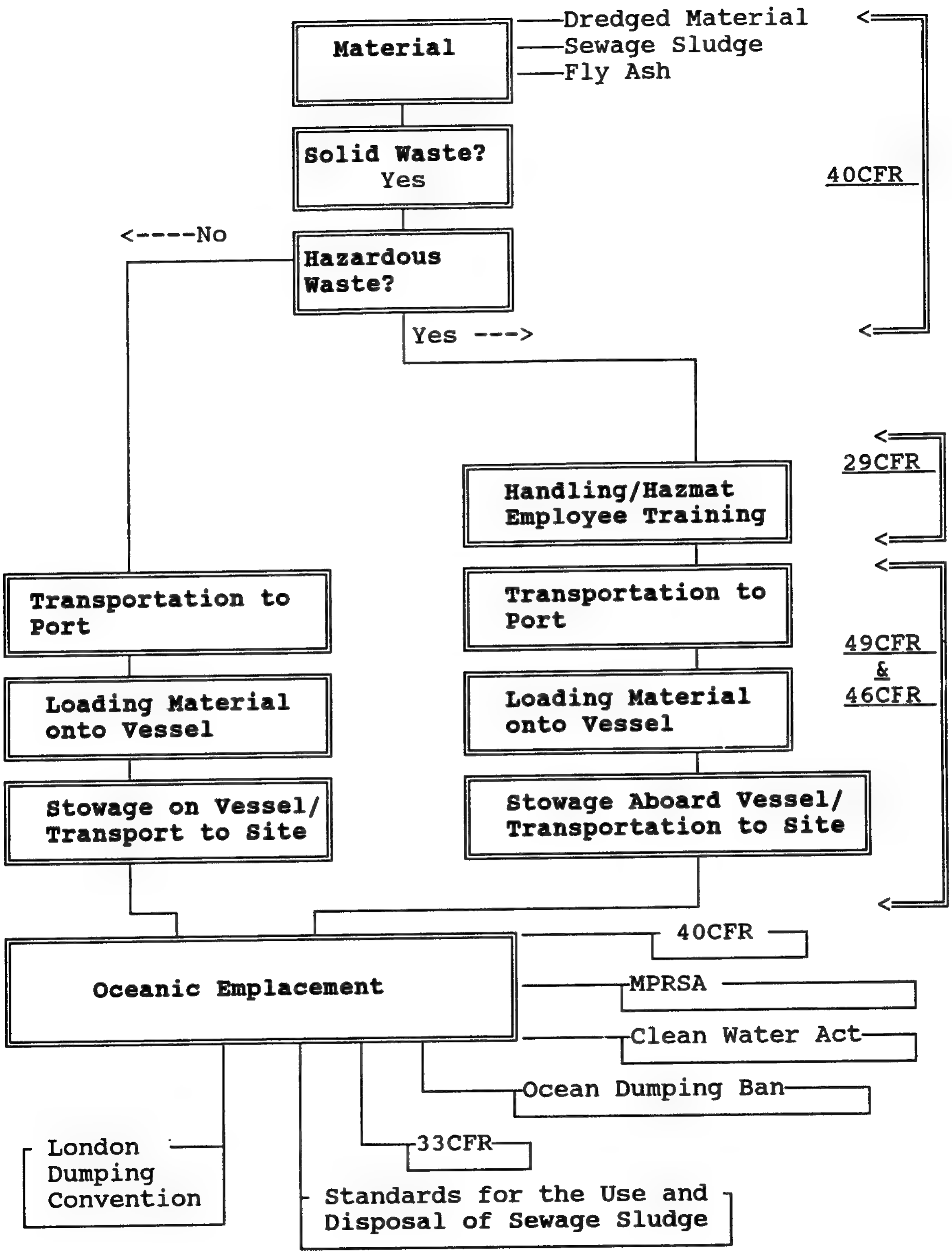

Figure 3.1-1 Condensed Environmental Regulatory Flow Diagram

Table 3.1-1 Environmental Regulations

	Hazardous Waste Handling	Sampling Methods/ Haz. Waste Classification	Hazardous Material Table/Lists	Dredged Material	Sewage Sludge	Fly Ash	Shipping Names, Packaging, Restrictions	Transportation (Trans to port and aboard vessel)	Oceanic Emplacement (Site Mgmt, Permitting)	* Legal/ Enforcement
40 CFR Protection of Environment		260, 261 (app)	261 (subpart D)	225, 230 232, 233	257, 261-268, 501 subpart O	266	261 subpart D	261 subpart D	220-225, 228,270	30.1100
49 CFR Transportation			172.101, 172.102				172, 173, 176, 177	100-177		
London Dumping Convention									■	
Resource Conservation and Recovery Act (RCRA)						6921 6924	6923		6921, 6924, 6925, 6928	6925, 6928, 6971
Marine Protection Research & Sanctuaries Act (MPRSA)					Ch 27 1414b				Ch 27	Ch 27 1414, 1416-1420
Superfund Amendments and Reauthorization Act (SARA)										9607-9609
Clean Water Act				1293, 1344	1345, 1362				1342-1345	1319,1365, 1367
58FR 9248 Standards for use or Disposal of Sewage Sludge					■					
33 CFR Navigation & Navigable Waters				323					323	
46 CFR Shipping								147-151		
29 CFR Labor	1910.120									
Clean Air Act						7473			7414	7413, 7420
MIL-HDBK-1005/8					47, 48, 62, 154-181			177		

■ Entire Regulation
* Not included in flowchart because not applicable to system level requirements.

3.2 WASTE STREAM CHARACTERISTICS

Research of waste stream properties was begun with definitions of the three waste streams the system will have to handle.

Dredged Material - As defined in 40 CFR 227.13, "Bottom sediments or materials that have been dredged or excavated from the navigable waters of the United States. Dredged material consists primarily of natural sediments or materials which may be contaminated by municipal or industrial wastes or by runoff from terrestrial sources such as agricultural lands."

Sewage Sludge - As defined in 40 CFR 257.2, "Sewage sludge means solid, semi-solid, or liquid residue generated during the treatment of domestic sewage in a treatment works. Sewage sludge includes, but is not limited to, domestic septage, scum or solids removed in primary, secondary, or advanced wastewater treatment processes; and a material derived from sewage sludge. Sewage sludge does not include ash generated during the firing of sewage sludge in a sewage sludge incinerator or grit and screenings generated during preliminary treatment of domestic sewage in a treatment works."

Municipal Incinerator Fly Ash - Defined in 40 CFR 240.101, Fly ash (suspended particles, charred paper, dust, soot, and other partially oxidized matter carried in the products of combustion) remaining after the incineration of municipal solid waste (normal residential and commercial solid waste generated within a community).

Compiled results from the research on the physical and chemical characteristics of the three waste streams are listed in Table 3.2-1. Apparent in the table, candidate APWI systems must be able to handle, transport, and emplace wastes exhibiting a wide range of properties. Some of the wide ranges that will have to be addressed when designing a system are in:

- Bulk Specific gravity,
- Solids content,
- Percent volatile matter in solids, and
- Particle sizes.

Another design constraint that will have to be considered in system design is methane gas production by microorganisms in sewage sludge.

Annual quantities generated of the three waste streams are listed in Table 3.2-2. The total quantity of waste generated annually is listed in the middle column. The right column lists volumes of waste estimated available for isolation by APWI. Annually 400 million metric tons of material is dredged, but only 5% or 20 million metric tons is contaminated (EPA 1993). APWI will be needed to handle only the contaminated sediments; "clean" sediments can be disposed of now in the oceans in designated areas and often can have beneficial use such as beach nourishment. By converting the dry weight of sewage sludge to wet metric tons, assuming an average of 20% solid content (Table 3.2-1), an annual volume of 26.5 million wet metric tons is calculated. The volume of sewage sludge applicable to APWI will be the total annual wet volume, or 26.5 million metric tons. As a result of a recent Supreme Court decision (City of Chicago et al. vs. Environmental Defense Fund, May 2, 1994), all municipal incinerator fly ash will be susceptible to testing for hazardous materials. Since all municipal incinerator fly ash is potentially hazardous, the total annual volume (1.5 million metric tons) is assumed applicable to isolation by APWI in this technical assessment.

Since sewage sludge is only slightly heavier than seawater, it is recommended that it be mixed with fly ash

to obtain a nominal bulk specific gravity of 1.25, similar to that of dredged material. Sewage sludge at 20% solids has a slurry bulk specific gravity of 1.04; fly ash at 85% solids has a slurry bulk specific gravity of 2.04.

To obtain a nominal slurry bulk specific gravity of 1.25, four parts sewage sludge will be combined with one part fly ash:

$$(4 \text{ X } 1.04 + 1 \text{ X } 2.04)/5 = 1.24$$

Although the total annual quantity of sewage sludge is far greater than four times the amount of fly ash, the coastal states have the heaviest concentration of municipal waste incinerators making this ratio obtainable in those areas. For the Port of New York vicinity, if a fifty mile radius is examined, the ratio of sewage sludge to fly ash is 5:1. If the radius is expanded to 100 miles for fly ash, the sewage sludge to fly ash ratio is 3:1 (Berenyi and Gould 1993) and (EPA 1992 (based on 47 dry lbs/sewage sludge /person/day)). Ribbon blenders, which are hoppers with a heavy shaft and paddles can be used to mix sewage sludge and fly ash at the port.

Table 3.2-1 Physical and Chemical Properties

	Dredged Material	Sewage Sludge	Fly Ash
Bulk Specific Gravity (By Weight)	1.25	1.04****	2.04
% Solids Content	32%	20%*	85%
% Volatile Material in Solids	varies	60-80% (raw) 30-60% (digested)	
% Organic	10%	35-80% **	<1-15%
% Insoluble in Water		90-95%	<.3%
% Ignition Loss			.8-16%
Size of Particles	silt 3.9-63.5um sand 625-2,000um gravel 2,000um		1-1,000um
Composition	sand, silt, & other sediments. (range of contaminants varies w/source)	55% elemental C	50% SiO_2
Energy/lb		6,000-12,000 BTU/lb (raw) 3,000-6,000 BTU/lb (digested)	n/a
pH	n/a	5-8	
Misc		Odor/pathogens, Gas production***	

* Location of water %: the 80% water is adsorption/internal

** 35% if digested.

***Gas analysis methane 0-75%

****Sewage sludge and fly ash can be mixed to obtain a specific gravity of 1.25

Table 3.2-2 Annual Quantities of Waste Streams Generated

WASTE STREAM	TOTAL QUANTITY OF WASTE GENERATED (MILLIONS OF METRIC TONS)	TOTAL QUANTITY OF WASTE APPLICABLE TO APWI (MILLIONS OF METRIC TONS)
DREDGED MATERIAL	400[(1)]	20[(5)]
SEWAGE SLUDGE	5.3 (DRY)[(2),(3)] 26.5 (AT 20% SOLID)	26.5[(2),(3)]
INCINERATOR FLY ASH	1.5[(4)]	1.5[(4)]

(1) Marine Policy Center, Woods Hole Oceanographic Center, 1991.

(2) Environmental Protection Agency, 1993.

(3) Based on 47 dry lbs sewage sludge/person/day at 20%.

(4) Berenyi and Gould, 1993.

(5) Zarba, 1989

3.3 WEATHER/SITE REQUIREMENTS

To begin technical assessment of the APWI emplacement concepts, to operate effectively, transit conditions from port to site and site characteristics must be quantified. The APWI project team selected five surrogate emplacement sites as shown in Figure 3.3-1 for which the required environmental data were generated..

Figure 3.3-2 illustrates the operational availability of a hypothetical APWI system at these five sites, when designed to operate in sea state 4 and sea state 5. Note that there is roughly a twenty percent increase in operational availability when a system is designed to operate in sea state 5 versus sea state 4. To maximize operational availability, OTECH selected sea state 5 as the operational requirement.

Table 3.3-1 lists the distances from potential APWI ports to the five surrogate sites. Three Alaskan ports are listed but were later excluded from consideration due to their distance to an emplacement site.

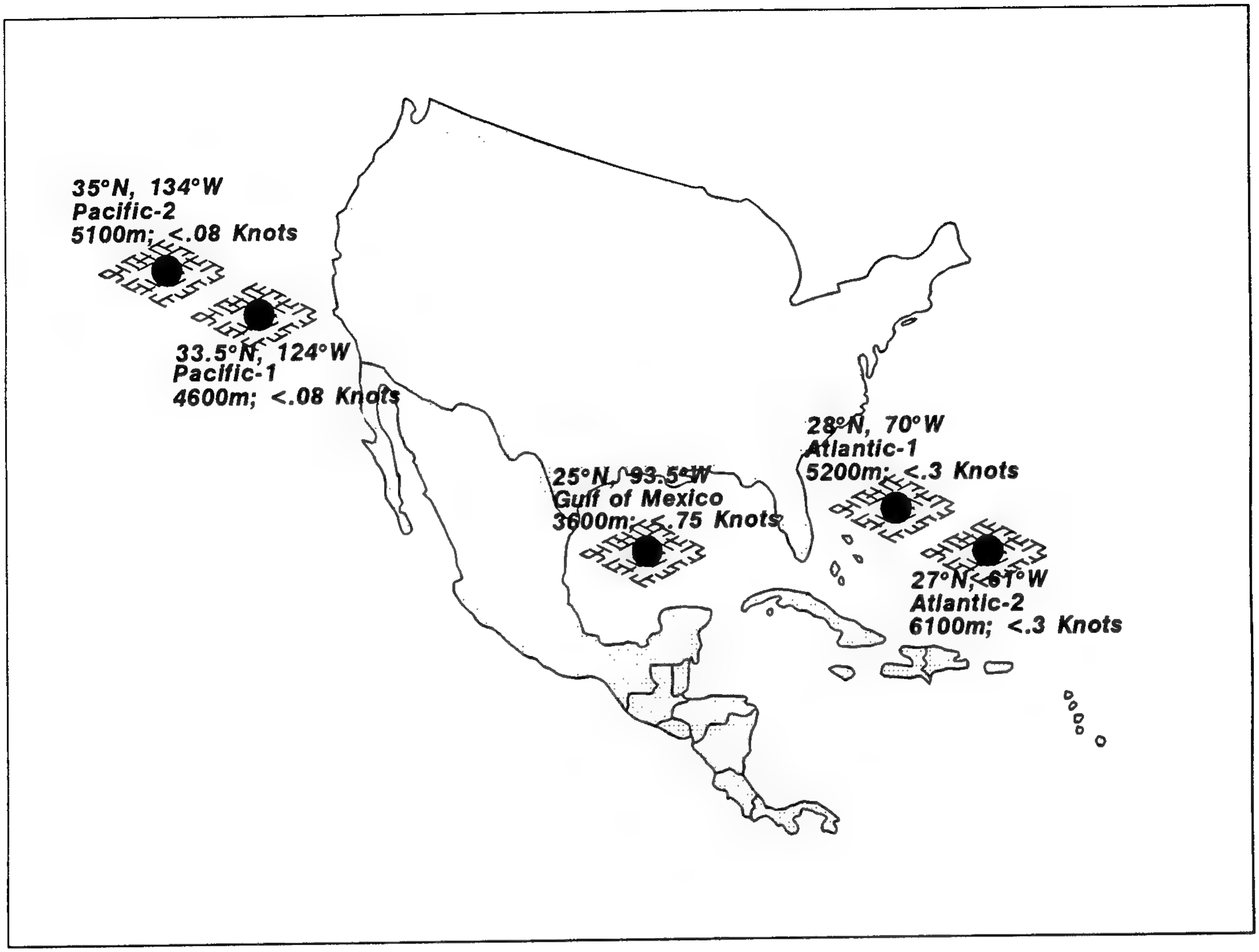

Figure 3.3-1 APWI Surrogate Site Locations

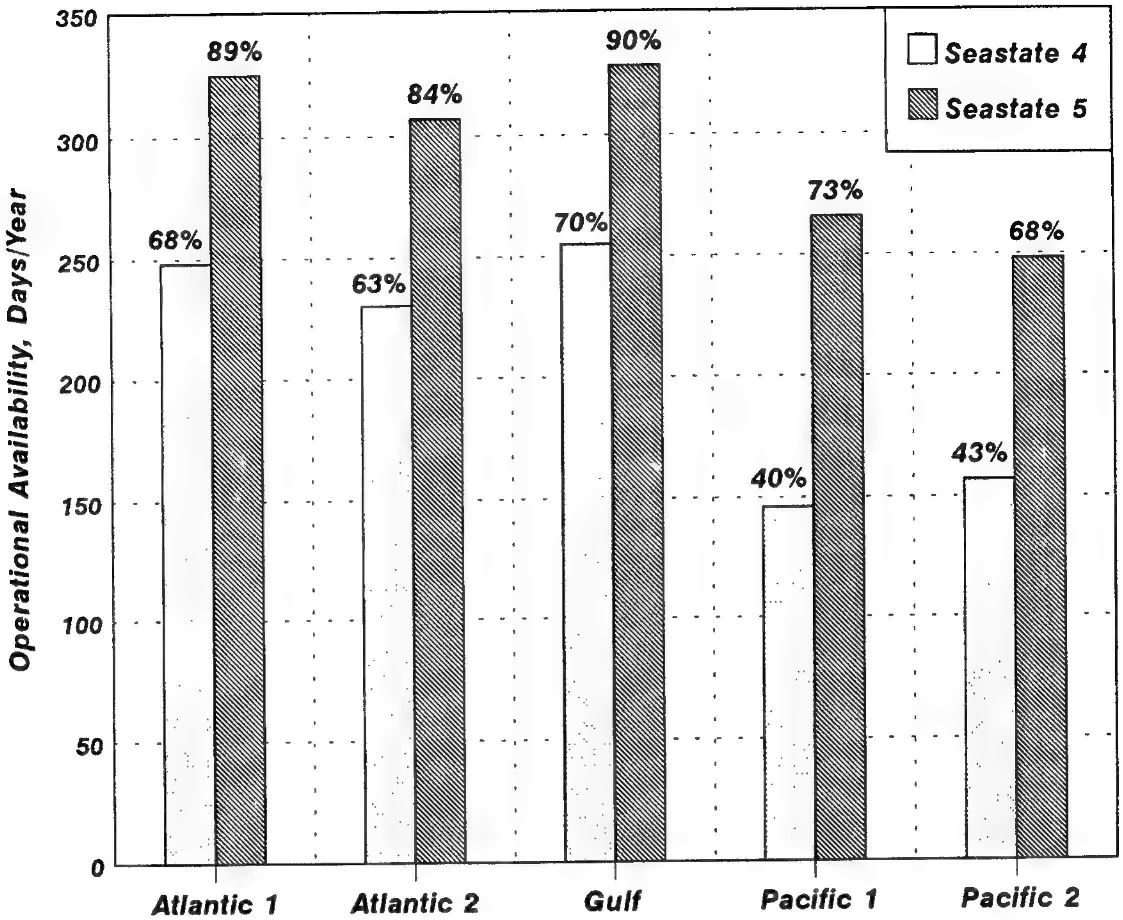

Figure 3.3-2 APWI Surrogate Sites-Operational Availability versus Sea State

Table 3.3-3 Tabulation of Candidate Port to Surrogate Site Transiting Distances

ATLANTIC SITES

PORT	DISTANCE TO SITE ATLANTIC 1, (28°N,70°W)	ATLANTIC 2, (27°N,61°W)
Boston	1600 km (864 nmi)	1937 km (1046 nmi)
New York	1458 km (787 nmi)	1935 km (1045 nmi)
Philadelphia	1404 km (758 nmi)	1937 km (1046 nmi)
Baltimore	1392 km (752 nmi)	1985 km (1072 nmi)
Norfolk	1159 km (626 nmi)	1817 km (981 nmi)
Wilmington, NC	1025 km (553 nmi)	1806 km (975 nmi)
Charleston	1089 km (588 nmi)	1930 km (1042 nmi)
Savannah	1157 km (625 nmi)	2017 km (1090 nmi)
Jacksonville	1158 km (625.nmi)	2043 km (1103 nmi)
Port Canaveral	1037 km (560 nmi)	1931 km (1042 nmi)
Miami	1038 km (561 nmi)	1912 km (1032 nmi)
Mean Distances	1229 km (664 nmi)	1932 km (1043 nmi)

GULF OF MEXICO SITE

PORT	DISTANCE TO SITE 25°N,93.5°W
Tampa	1146 km (619 nmi)
Gulfport	736 km (398 nmi)
Galveston	495 km (495 nmi)
Brownsville	405 km (219 nmi)
Mean Distances	696 km (376 nmi)

PACIFIC SITES

PORT	DISTANCE TO SITE PACIFIC 1, 33.5°N,124°W	PACIFIC 2, 35°N,134°W
Anchorage	3593 km (1939 nmi)	3124 km (1687 nmi)
Valdez	3463 km (1870 nmi)	3033 km (1638 nmi)
Kodiak	3444 km (1854 nmi)	1876 km (1553 nmi)
Port Angeles	1626 km (878 nmi)	1700 km (918 nmi)
Seattle	1577 km (851 nmi)	1704 km (920 nmi)
Vancouver	1353 km (730 nmi)	1519 km (820 nmi)
Portland	1346 km (726 nmi)	1511 km (815 nmi)
San Francisco	499 km (270 nmi)	583 km (1081 nmi)
Port Hueneme	447 km (241 nmi)	1354 km (731 nmi)
Los Angeles	531 km (286 nmi)	1448 km (782 nmi)
San Diego	636 km (343 nmi)	1565 km (845 nmi)
Mean Distances	1002 km (541 nmi)	802 km (1485 nmi)

3.4 SYSTEM PERFORMANCE REQUIREMENTS

Table 3.4-1 summarizes general performance and operational requirements that any viable APWI system must meet. Detailed descriptions of these categories are included in Section 4.5 of the System Requirements Report.

Table 3.4-1 System Performance/Operational Requirements

1. System Capability:
   a. 2.5 million metric tons/yr. per port
   b. Maximum transiting distance to Atlantic; Gulf; or Pacific APWI sites from any coastal port <1852 km (1000 nmi)
   c. No exposure of waste stream products to intervening water column, including leakage and spill prevention design features
   d. Static electricity dissipation design features
   e. Validation and verification
   f. Range safety design features

2. Transiting speed: 6.2 m/s (12 knots), minimum

3. Operational depth: 6700 m, maximum

4. Emplacement accuracy: within 500 m X 500 m box

5. Reliability: MTBF > TBD

6. Maintainability: MTTR < TBD

7. Environmental:
   a. Operational: Sea state 5 conditions
   b. Survivability: Sea state 8 conditions
   c. Currents: <0.78 m/s (1.50 knots) on surface; <0.39 m/s (.75 knots) on Abyssal Seafloor
   d. Hydrostatic pressure: <6.2 X 10^7 Pa (9000 psig)
   e. Temperature: 0° C to 49° C

8. Waste Stream Compatibility: (Non-Hazardous)
   a. Contaminated dredged materials: 32% solids by weight
   b. Sewage sludge: 20% solids by weight
   c. Municipal fly ash: 85% solids by weight

9. Design Requirements:
   a. American Bureau of Shipping
   b. Code of Federal Regulations 33, 40, 46 & 49 CFR
   c. Safety of Life At Sea (SOLAS)
   d. American Petroleum Institute API RP 2A
   e. Interface Std. for Shipboard Equipment, DOD STD-1399

4.0 TECHNICAL ASSESSMENT OVERVIEW

The purpose of the technical assessment was to identify, refine, and evaluate options of material preparation, transportation, and emplacement of dredged material, sewage sludge, and municipal incinerator fly ash on the abyssal seafloor.

Potential options or concepts of abyssal emplacement were initially identified by performing a broad-based patent search of existing technologies and concepts of abyssal seafloor isolation. Since this approach generated a large number of concepts, a trade-off analysis was used to narrow the number down to the best concepts applicable to APWI. As a result of the down-selection from 128 to seven "winning concepts", followed by the synthesis of these seven, five APWI concepts were chosen to further define and evaluate. These concepts are:

- Surface Emplacement - A customized barge is designed with 51 separate cells, which are lined with disposable, high strength, high density, flexible fabric bags. The waste material is loaded into the individual bags, which are closed before leaving port. The vessel then transits to the APWI site, opens the trap doors to the cells to release the bags, which free-fall to the seafloor. The bag isolates the material from the intervening water column during descent. After impact with the bottom, the waste material remains contained in the bag. Experiments conducted by the Army Corps of Engineers has demonstrated that these types of bags do not burst upon impact with the seafloor.

- ROV Glider - A submersible vessel (ROV Glider) is used to transport material to the abyssal isolation site, submerge, release the waste at a specified altitude above the seafloor, and return back to the ocean surface for recovery. Similar to Surface Emplacement, the Glider contains individual compartments lined with flexible bags. The Glider is negatively buoyant when loaded with waste, so it is towed to the APWI site in a barge. At the site, the ROV Glider is released from the barge and descends in an actively controlled, spiral-shaped flight path until it nears the seafloor. Then trap doors open, the containerized load falls out, and the now positively buoyant Glider returns to the surface. The ROV Glider is then recovered by the surface ship into its transporter barge. The ROV Glider is autonomously controlled, but can be minimally controlled from the surface as a backup mode.

- Direct Descent Disk - A vessel in the shape of a shallow disk with a large diameter delivers its cargo to a predetermined altitude off the seafloor and then releases it. The disk also has numerous cargo cells lined with bags. A disk is negatively buoyant when loaded with waste, so it is transported to the site in a "floater module." At the APWI site, the disk is released, descends in a near-vertical path to near the seafloor, brakes, releases its containerized load via trap doors, becomes positively buoyant, and ascends to the surface. In contrast to the ROV Glider, the Direct Descent Disk does not follow a closed-loop controlled glidepath. Its inherently stable hydrodynamic design allows it to perform the operation without active stabilization.

- Pipe Riser - A set of four large diameter pipes run vertically from the ocean surface to near the seafloor to transport waste to the abyssal isolation site. A transport ship hauls the waste material in bulk from the port to the APWI site, where it is pumped to the Riser for dilution with cold water prior to emplacement. Two pipes bring cold water from 700 m depths to slurryize and thermally equalize the waste with the seafloor temperature. The slurryized waste travels down the other two pipes, isolating the waste from the water column. The waste material is discharged to form a mound on the seafloor. The Pipe Riser is dynamically positioned at the top and moored at the bottom to maintain station.

- Tethered Container - A ship is loaded with bulk waste at port and transits to the APWI site. A large on-board rigid container, loaded with the bulk waste, is winched from the ship to near the seafloor. At this point, the bottom of the container is opened and waste falls out to form a mound on the seafloor. The container is then winched back to the ship for another batch load.

Along with the issues unique to each concept, some issues are common to all concepts. These common issues include:

- Transporter System:
  Research of geographical waste stream distribution and existing port facilities has determined that a bulk carrier ship of 25,000 DWT capacity would be suited for use in all US coastal regions. These ships would be capable of 15 knot speeds with a range in excess of 2000 nmi.

- Handling Systems:
  Mechanical handling systems have the capability of loading any APWI concept at 4800 metric tons/hr.

- Waste Stream Containers:
  Flexible bags were chosen to encapsulate the waste material for three of the concepts.

- Port Facilities:
  Research of existing U.S. port facilities and docking spaces yielded 125 candidate docking sites large enough for the APWI concepts.

- Applicability of APWI Concepts with Waste Streams:
  The three waste streams each have different physical characteristics that must be accommodated by the APWI concepts. An effort was made to minimize the amount of waste stream preprocessing in order for the waste to be handled by the individual concepts. The most significant parameter was handling characteristics, dominated by percentage solids.

- Isolation Site Capacity:
  Storage capacity of 1.8 billion metric tons is based upon four hundred 500 m X 500 m square grids within a 10 km X 10 km designated site location, per Atlantic, Gulf of Mexico, or Pacific APWI site location.

As each of the concepts was evaluated, many technical issues surfaced. These issues were identified and documented in the Technical Assessment Report. Depending on the complexity of the issue, some were resolved and other were not. A list of unresolved technical issues is provided in Section 8 of the Technical Assessment Report, along with the proposed method of solution. Each of the concepts require development of large scale marine equipment to handle the magnitude of the three waste steams.

The defined APWI concepts were compared to the system level requirements documented in the System Requirements Report. The Tethered Container concept was disqualified because a handling system capable of emplacing the required amount of waste per system per year was not technically feasible. All system level requirements can be met by the remaining four concepts.

Two independent reliability analyses, Fault Tree Analysis (FTA) and Failure Modes Effects and Criticality Analysis (FMECA), were performed on the remaining four APWI concepts. The results of these analyses provided a ranking of the four systems according to combined technical and operational risk. In increasing order of risk, they are:

- Surface Emplacement
- Direct Descent Disk
- ROV Glider
- Pipe Riser

Of the failure modes identified, all can be overcome by adding redundancy in the design. Areas requiring additional study, modeling and/or testing were identified for each concept as a result of the reliability analyses.

4.1 CONCEPT IDENTIFICATION/DOWN-SELECT PROCESS

OTECH has performed previous studies in deep ocean isolation and has completed, under Internal Research and Development (IRAD) funds, a broad based patent search for ocean isolation concepts. This comprehensive patent search identified 128 ocean isolation technology patents. The patents ranged in complexity from individual pieces of ocean isolation technology to entire isolation systems incorporating many pieces of technology. The patents were dated from 1895 to present. Thirty of these 128 patents were comprehensive summarizing the other 98 as prior art. A one-page pictorial and summary of each of these 30 patent concepts are included as Appendix A of the Technical Assessment Report.

These 30 concepts were then critiqued against the evaluation criteria shown in Table 4.1-1. These evaluation criteria all fit within three major issues: engineering feasibility, environmental soundness, and cost effectiveness. Even though this is an engineering study, environmental and cost considerations must be addressed, at least at a qualitative level, to evaluate any concept as a system.

Table 4.1-1 APWI Concept Evaluation Criteria

#	Criteria	Definition
1	Bulk Waste Potential Exposure to Water Column	Concept's ability to isolate the material from the intervening water column on its descent to the abyssal seafloor.
2	"In Transit" Bulk Waste Containment Integrity/Stability	Concept's ability to keep waste containerized or keep waste from shifting, leaking or spilling during transit.
3	Bulk Waste "As Deposited" Integrity/Stability	Concept's ability to deposit material in such a manner that mounds will be stable or containers will stay intact.
4	Monitoring Ease via Site/Deposit Footprint	Concept's ability to consistently and discretely deposit material in the intended location where monitoring takes place.
5	Remediation Ease via Bulk Waste Deposit State	Concept's ability to emplace material in discrete mounds or containers allowing remediation to occur.
6	Loading/Unloading Ease	Concept's ability to be loaded with existing loading equipment in a timely manner.
7	Transport Ease	Concept's ability to employ conventional design bulk material transporters.
8	Emplacement Ease	Concept's ability to consistently, rapidly, and accurately emplace material on the abyssal seafloor.
9	Reliability/Maintainability (Availability)	Concept's ability to be available whenever needed.
10	Hazard Potential to Navigation	Concept's port operations, transiting to site, and site operations interference with commercial or recreational navigation.
11	Near Shore/Open Ocean Weatherability (Survivability)	Concept's ability to withstand severe weather without loss of APWI concept.
12	Extrapolation from Current Technology(s) (Performance/Operational Risk)	Concept's similarity to technology being successfully used.
13	Developmental/Demonstration Program Time Duration (Experimental/Validation Risk)	Concept's experimental steps necessary to prove it is safe and effective for real operation.
14	Bulk Waste % solids Range Capability ("As Delivered" to Port/Staging Area)	Concepts's ability to work with waste stream products at varying percentage solids or the need for a certain pretreatment.
15	Transport Cost: Port to Site	Cost of transporting the waste streams to the APWI site including consumables and maintenance.
16	Emplacement Cost: Site to Seafloor	Cost of operating concept at the emplacement site including consumables and maintenance.
17	Monitoring Cost: Waste Stream versus Site/Biota Impact	Cost of monitoring effects of candidate's emplaced waste.
18	Capital Asset Cost: Transport/ Emplacement/Monitoring	Cost of candidate waste handling equipment.
19	Port Facility Cost: Staging/Docking/ Handling	Cost incurred during port-side operations including, docking costs, cost of use of handling system, and utilities.
20	Personnel Cost: Training/Labor Skill Category/Etc.	Cost of training/hiring appropriate skill level for technology, number of employees needed, environmental training.

The result of this evaluation, followed by combining similar approaches, led to the following five concepts:

1. Surface Emplacement - Bagged waste is released from the surface and allowed to free fall to the seabed. Rationale behind this concept is that with known currents and the stable free-fall bag shape, it is possible to predict the location of the container on the seabed within a 500 m x 500 m area.

2. ROV Glider - Controlled descent of a Glider to near the seafloor. The bagged load is released and falls to the seafloor. The Glider, then buoyant, returns to the surface.

3. Direct Descent Disk - Direct autonomous vertical descent of a Disk to near the seafloor. The Disk brakes and the bagged waste is released and falls to the seafloor. The Disk, then buoyant, returns to the surface.

4. Pipe Riser - Set of two large diameter pipes running vertically from the surface of the water to near the seafloor. Two other pipes bring water up from 700 m depths to dilute slurryized waste. Additionally, this dilution is critical to achievement of a low bulk specific gravity slurry, such that the resultant static head on the discharge riser is not too large so as tc generate excessive gravity flow rate in the dispersion pipe. Mixing in cold seawater from 700 m depth also greatly reduces the potential for a thermal plume. The slurryized waste travels down two pipes isolating it from the water column and is discharged near the seafloor.

5. Tethered Submersible Container - Large waste pay loads are winched from the surface to be released near the seafloor. The container is sealed to eliminate contact with the water column. The bottom of the container opens near the seafloor expelling waste.

Each of these concepts was utilized as the basis or starting point for detailed conceptual design. In the initial examination of the winning concepts and the synthesis process, certain issues were present and basically identical between the concepts. These common elements are:

- Transporter System - Taking into consideration the transiting distances, waste stream volumes, and transiting speeds identified in the System Requirements Report, selection of the optimum transporter size and type was made.

- Handling Systems - Given the volume and physical state of the waste streams entering the port, the size and type of handling system needed to load the APWI vessel was determined.

- Waste Stream Containers - Based on the needs of each concept, the ideal material, size, and shape of containers was defined.

- Docking Space - Given the port locations identified in the System Requirements Report and the size of the transporter chosen for the APWI concepts, existing docking spaces and associated equipment for the APWI concepts were identified.

- Interface of APWI System with Waste Streams - Taking into consideration the generation method and normal preprocessing steps for the three waste streams (dredged material, sewage sludge, and municipal incinerator fly ash), the physical state (percentage solids and specific gravity) of the waste when the APWI System receives them was determined.

- Isolation Site Capacity - Storage capacity in a 500 m X 500 m isolation site based on predicted mound geometry was calculated.

4.2 CONCEPT DESCRIPTIONS

The five APWI concepts are summarized in the following sections. Each concept is focused upon a specific method for emplacing large tonnages of waste into designated APWI sites. This waste is delivered by transport vessels operating from various coastal ports to designated APWI sites located in the Atlantic, Gulf of Mexico, and the Pacific, all within 1850 km (1000 nmi) of the various ports. These designated isolation sites, approximately 10 km x 10 km, consist of up to 400 local sites approximately 500 m x 500 m. The 500 m X 500 m isolation site will facilitate the ability to monitor the site's chemical, biological and physical state.

4.2.1 SURFACE EMPLACEMENT

The Surface Emplacement concept is illustrated in Figure 4.2.1-1. As explained in detail in Section 5.1.1 of the Technical Assessment Report, an Integrated Tug/Barge (ITB) with trap doors was selected as the concept baseline. The barge cargo capacity was sized for 25,000 DWT consisting of 51 individual cargo bays. These cargo bays would be lined with flexible, disposable bags. Wet filling (cargo bays free-flooded) is desired to minimize stresses on the bag during filling. Use of the disposable bags assures that the bulk waste is isolated from the intervening water column during the free-fall descent from the surface to the seafloor. The dimensions of the barge are roughly:

- Length overall (OA) of 214 m (700 ft); Length at waterline (WL) of 207 m (680 ft); Beam of 32 m (106 ft); Draft of 7.3 m (24 ft); Depth of 12.8 m (42 ft); & Displacement of 39,000 metric tons.

The overall length with an integrated tug would be approximately 236 m (775 ft). Ship/barge sizes and performance characteristics for the Surface Emplacement concept were determined by John J. McMullen Associates, Inc. (JJMA) and are documented as Attachment 1 in the Technical Assessment Report.

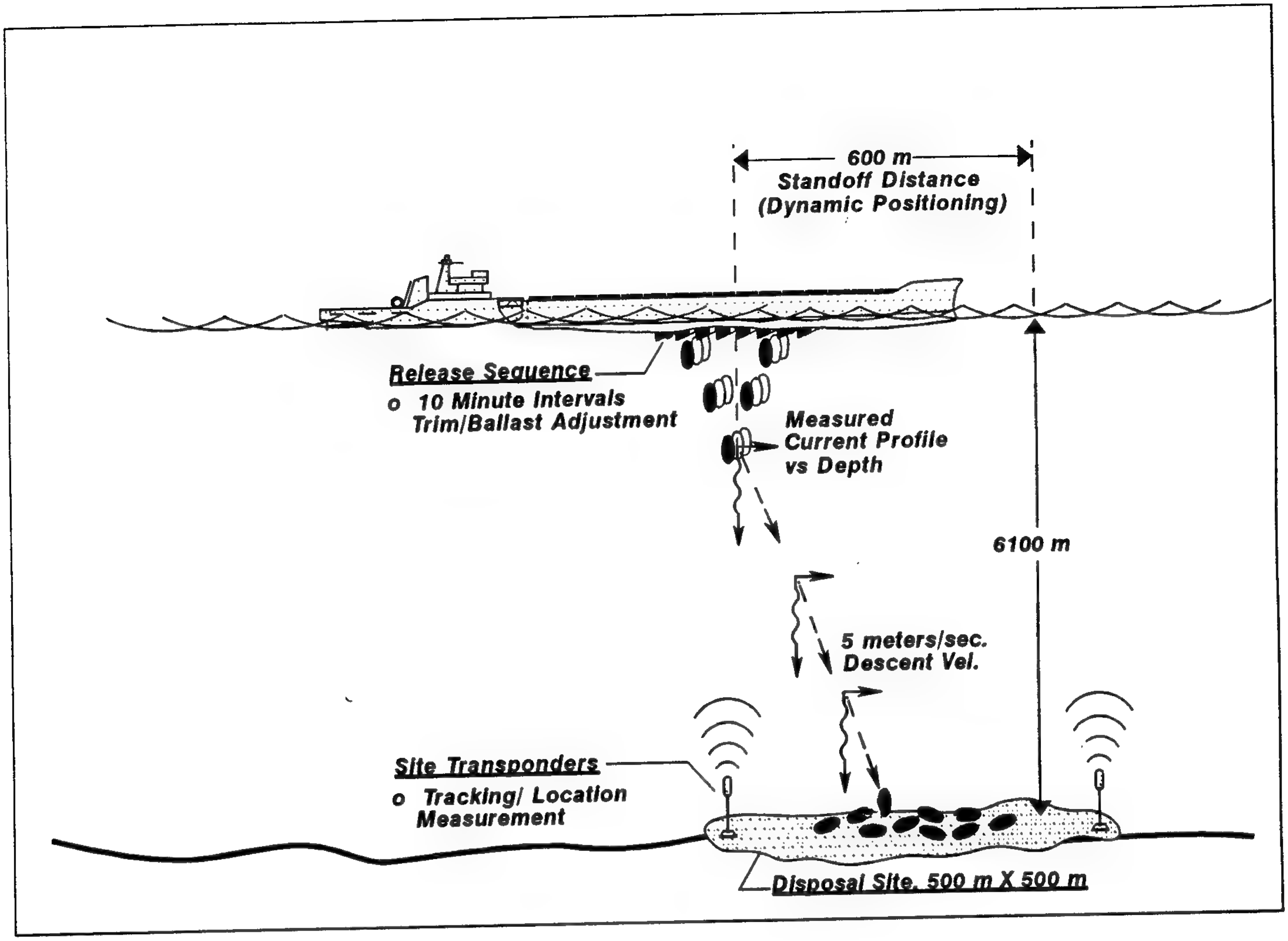

Figure 4.2.1-1 Surface Emplacement Concept uses 50 ea. 382 m^3 Capacity Geotextile Bags for Deposit of 25,000 Metric Tons Bulk Waste into 500 m X 500 m Monitored APWI Disposal Sites

Surface Emplacement Operational Description

The operational scenario for Surface Emplacement, once on site, is illustrated in Figure 4.2.1-2 and described below.

- The transporter arrives on-site, identified by an on-board navigation/global positioning system, and dynamically positions to a predefined standoff distance for release of the bagged waste. The standoff distance adjusts for bag freefall current-induced drift. This standoff distance is based upon previously established or real-time knowledge of current conditions existing throughout the water column. The free-fall descent terminal velocity of the bags is estimated to be 5.0 m/s.

  For an abyssal seafloor site located at 6100 m depth, a standoff distance of approximately 600 m and an "average" current at the site of approximately 0.5 m/s, the expected emplacement watch circle from a single cell would be 50 m in diameter. This calculation is based on the drift range of bags falling at +/- 10% of the nominal terminal velocity, 4.5 m/s and 5.5 m/s. Since cargo bays span a distance of approximately 160 m, and assuming that the vessel maintains station-keeping standoff distance, the minimum emplacement watch circle would be a 210 m diameter target area Physical modelling is required to accurately determine bag drift variability in order to determine if this watch circle is achievable.

- The transporter interrogates previously deployed and located bottom transponders to confirm its relative position with respect to the site and the status of the bottom transponders within the site range. A deployable transponder is released, having a nominal terminal velocity of approximately 5 m/s. The transporter confirms that the transponder has landed within the targeted area, confirming that the desired standoff distance has been achieved. If not, adjustment is made to the vessel's relative position and a second transponder is released. The required time for the first (and any subsequent trial) is less than 25 minutes before commencement of the next step.

- The transporter commences emplacement operations by opening the hull trap doors in pairs of rows, starting in the middle of the ship and working simultaneously toward the bow and stern.

  One bag per row could be outfitted with a transponder for tracking its descent and final location. These transponders would be inexpensive throw-away units. The final position could then be logged by vessel personnel and maintained in permanent files for long term emplacement site management.

  The waste bags are expected to survive landing on the seafloor without rupturing, based on the Army Corps of Engineers (COE) testing of geotextile bags of similar size and weight. Details of this testing is contained in Attachment 2 of the Technical Assessment Report.

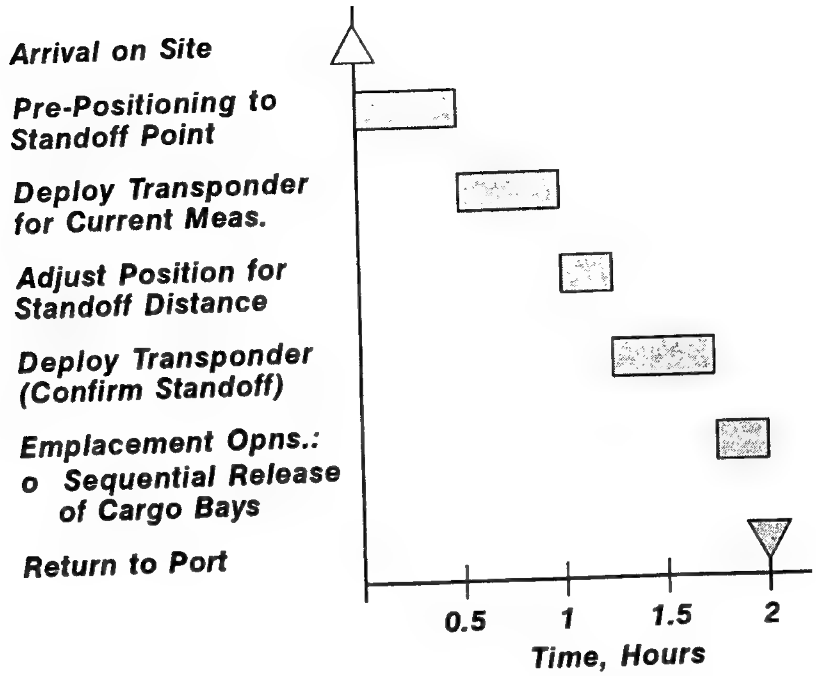

Figure 4.2.1-2 Surface Emplacement Operational Timeline

Surface Emplacement Key Technical Issues

- **Bag Hydrodynamics:**
  The fundamental technical issue to be addressed for Surface Emplacement is the hydrodynamic performance characterization of approximately 380 m^3 (500 yd^3) of bagged waste with varying weight in free-fall descent through a water column of up to 6100 m. Previous experience by the COE is only applicable to water depth of approximately 90 m, or less than 5% of the APWI requirement. Empirical testing will be required to quantify boundary condition constraints on variation in bag weight versus the measured watch circle scatter pattern, as would exist for the emplacement site currents, and to assess bag susceptibility to lateral drift (or side-slip) due to variations in hydrodynamic shape and asymmetric distributions of mass within the bags.

- **Bag Survivability:**
  Bag survivability upon seafloor landing will have to be determined for deep water emplacement. This includes the design of bag seams, any expansion joints, and the filler nozzle.

- **Cargo Bay/Trap Door Design:**
  Testing of similar types of geotextile bags conducted by the COE has found that the highest stresses on the bags occur during release from the barge. This stress point occurs as the bag squeezes out of the opening made by the split hull barge as it slowly opens. The conclusion is that the trap door/bag release mechanism for the surface emplacement concept must be designed to avoid stressing the bag as it exits the cargo bay. In addition, the cargo bays should be designed with low-friction side wall surfaces to facilitate rapid egress

of the bags. The size and shape of the cargo bays will determine the initial shape of the bag, and therefore the bag hydrodynamics. The bag hydrodynamics and the cargo bay design are directly coupled and will have to be analyzed together.

- **"Throw-away" Transponders:**
  Battery powered/multiple channel transponders will be required to assure that the bags are emplaced within the desired emplacement site monitoring area. The host platform must be capable of interrogation of a set of seafloor mounted transponder repeaters to determine the final location of individual groups of bags released from the surface. The "throw-away" transponders must provide short range (<500 m) signal strength capability to assure that the repeaters may register their arrival at the site location. Capability currently exists to provide up to 16 channels for interrogation of individual groups of bags.

- **Geotextile Bags:**
  Geotextile bags are presently being manufactured by two different vendors in the United States, with annual production volume for 380 m^3 (500 yd^3) capacity bags presently at 700 per year. The Surface Emplacement concept would require approximately 4900 bags of 510 m^3 (667 yd^3) capacity per year, or 7 times the current annual production rate. Discussions with the existing vendors, and other potential suppliers of similar product, are required to assure capability to meet revised form factor(s) and to realize the lowest overall production cost.

4.2.2 ROV GLIDER

The ROV Glider concept is illustrated in Figure 4.2.2-1. The transporter, described in detail in Section 5.2.1 of the Technical Assessment Report, will be an ITB with a 25,000 DWT cargo capacity. The concept consists of three primary elements: the Glider, the transporter barge, and the tug.

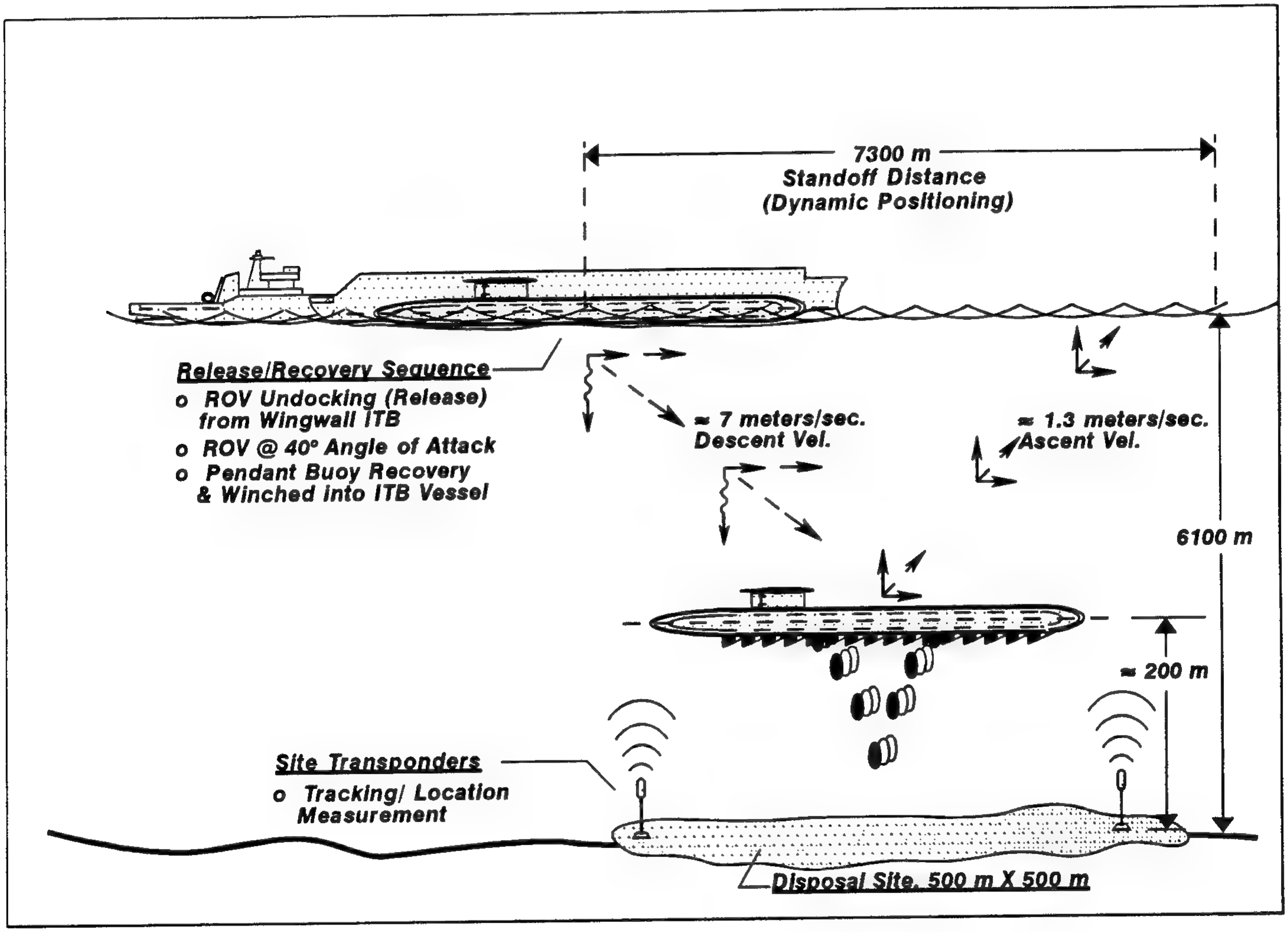

Figure 4.2.2-1 ROV Glider Concept Employs a 25,000 DWT Capacity Autonomous Vehicle to Descend to Abyssal Depths, Release Its Cargo, and Return to the Surface

The waste cargo, carried in the Glider, is contained in hexagonal cells forming a honeycomb of 153 cells arranged in six rows of alternating 26 and 25 cells per row. These cargo bays are lined with the same flexible liner as suggested for the Surface Emplacement concept. These liners are only filled to 75% capacity to allow for bag-waste deformation at landing on the seafloor as an energy absorption mechanism. Assuming a cargo specific gravity of 1.25, the fully submerged Glider weight is approximately 3900 metric tons. Upon cargo release, the vehicle has a positive buoyancy of approximately 500 metric tons.

The dimensions of the Glider are as follows:

- Length OA of 130 m (426 ft); Length WL of 129 m (423 ft); Beam of 30 m (98.5 ft); Draft (Unloaded) of 7.0 m (23.0 ft); Depth of 10 m (32.8 ft) and Displacement of 29,000 metric tons.

The ROV Glider is negatively buoyant when fully loaded and therefore must be transported to the emplacement site via a positively buoyant barge. The barge configuration uses twin hulls (similar to a catamaran) with an open space-frame deck structure span between the hulls. Dimensions of the barge are as follows:

- Length OA of 230 m (755 ft); Length WL of 222 m (728 ft); Beam of 43.9 m (144 ft); Draft (Loaded) of 7.0 m (23 ft); Depth of 15.2 m (50 ft), and Displacement of 20,150 metric tons.

The above Glider/barge characteristics were analyzed by JJMA. Details of this analysis are included as Attachment 3 of the Technical Assessment Report.

The ROV Glider would be supported by the barge during loading, transiting, and launching operations using ARTUBAR linkages (similar to the linkage used to connect the tug to the barge). These linkages would be located along the interior walls of the twin hulls, and engage the port and starboard faces of the Glider. The barge is capable of adjusting ballast to align the ARTUBAR linkages to the mating engagement features of the ROV Glider, either in port or at sea during recovery operations. Additionally, ballast adjustment is utilized to initialize launch conditions for the ROV Glider, whereby the Glider is fully submerged prior to being placed into an approximate 40° pitch down attitude. This 40° pitch down attitude is achieved by release of all the ARTUBAR linkages except for the aft-most pair, allowing the ROV Glider to commence pitch rotation about the aft pivot point. On-board attitude sensors trigger release of the aft linkages such that the desired ROV Glider angle-of-attack is achieved.

The following discussion is based upon supporting analysis provided by Dr. R.A. Barr, Hydronautics Research, Inc., to identify performance characteristics of the ROV Glider.

A stable glide path is achieved by proper longitudinal and vertical separation of the center of gravity (C_G) and the center of buoyancy (C_B) and by providing the appropriate tail surfaces. Roll stability is satisfied by locating the C_G below the C_B. A suitable vertical separation of these centers would be 1 to 2 percent of the beam or about 0.3 to 0.6 m. Dynamic directional stability is assured, even during the initial stages of the glide, by providing neutral or positive static ("weathervane") stability in the vertical (pitch) and lateral (yaw) planes. To achieve this positive static stability, the Glider has a horizontal stabilizer foil at its aft end. This stabilizer has a 30 m span and an 8 m chord, and is supported by vertical stabilizers with chords and heights (spans) of about 5 m and 8 m, respectively. The 8 m span allows sufficient clearance of the horizontal foil from the Glider's hull, thereby minimizing possible adverse flow interference. The use of a streamlined afterbody allows the horizontal and vertical stabilizers to be of acceptable size.

The desired glide path is achieved by adjusting the horizontal stabilizer's angle-of-attack. A stable glide will occur when total body axis hydrodynamic forces equal the components of net weight (weight minus buoyancy). The relationships between glide slope, glide speed, net weight in water, their dependence on the body drag

coefficient and net weight ratio are determined from the summation of forces in the Glider's surge and heave axis. Results of these summations demonstrate the following relationships:

- Glide slope increases and descent time decreases with an increasing body drag coefficient (C_D)
- Descent time decreases with increasing net weight
- Glide slope is independent of the net weight ratio

Finally, for operation at the minimum attainable glide slope considered desirable, (i.e., less than 45 degrees) glide speed (along the glide path) increases and descent time decreases with increasing net weight ratio.

Preliminary evaluations for various weight to buoyancy ratio (W/B), hydrodynamic drag coefficients, and varying glide slopes/angle-of-attack produce a vertical descent velocity of approximately 7 m/s. This would result in the ROV Glider requiring approximately 15 minutes to reach an emplacement site located at 6100 m depth. The equivalent ascent velocity is estimated at approximately 1.3 m/s, requiring approximately 78 minutes to return to the surface.

ROV Glider Operational Description

The following sequence of events delineates the emplacement of waste at an APWI site using the ROV Glider:

- An ITB transporter arrives at the APWI site utilizing global positioning system (GPS) navigation and proceeds to an appropriate standoff location for launching the ROV Glider. The standoff distance is based on previous or real-time knowledge of currents throughout the water column as well as the planned glide path slope. While on its descent, the Glider, due to its ability to dynamically adjust its course toward the final emplacement site, will be able to correct for current drift. For a weight to buoyancy ratio of 1.25, a C_D of 0.25, and a glide path angle of 40 degrees, the speed along the path will be about 10.9 m/s. The vertical descent velocity is 7 m/s, resulting in a descent time to the cargo release depth of 6100 m of only 15 minutes. As the Glider nears the 200 m altitude above the seabed, where it releases its cargo, the horizontal (forward) speed is about 8.3 m/s.

  Primary Glider control will be on-board using preprogrammed flight plans with adaptive control; however, limited surface control can be accomplished using acoustic links. Conventional Ultra Short Baseline (USBL) sonar navigation equipment can track the departure from the surface ship and the arrival of an approaching beacon. Since the vehicle will be following a preset glide path, its depth profile will be known, so the USBL navigation fixes can be verified or corrected for slant ranges by on-board processors. Since accurate navigation within close proximity of the emplacement site may not be possible due to shadowing and reflections from waste containers, an extended approach path can be established outside the drop zone. The approach path can be marked with passive reflectors of the Glider's own sonar by using an active array of long baseline transponders. This extended run permits locking in a final acoustic position. Last minute course corrections for a specific drop site can then be made via inertial dead reckoning.

- As the cargo cells begin sequential release, the Glider begins pitching up and gaining buoyancy. On board electronics record the location of the drop as well as the individual status of each cargo cell.

- Following the release of the remaining cargo, the Glider eventually loses its forward momentum and begins to ascend due to its positive buoyancy. The rate of ascent is determined by the drag on the Glider which in turn is dependent on the Glider's attitude during the ascent. If in its lightship state, it is evenly trimmed, then the drag will be greatest and the ascent rate will be about 1.3 m/s. Therefore the Glider will surface in about 78 minutes. By altering the trim to a bow or stern up attitude, drag will be reduced and ascent rate increased. The optimum ascent rate can be determined in a later study. The ascent of the Glider will trigger

the release of the pendant buoy system housed in the stern fairing of the Glider. Although the Glider's ascent will be tracked on the ITB's sonar to avoid collision, the buoy will serve as a mechanical adjunct to visually warn of the Glider's impending surfacing. The pendant buoy would also contain a transponder for the ITB to observe its ascent offering further tracking redundancy. A minimum safety zone can be established based on the length of the buoy's tether. For example, a 1500 m tether would dictate to surface vessels a minimum safe standoff distance of 1500 m from the pendant buoy. Sighting of the buoy would indicate Glider re-surfacing in about 19 minutes. The buoy will always precede the Glider because of its lower drag.

- Once the Glider has surfaced, the pendent buoy can be retrieved and used as a tag line to winch the Glider back onto the carrier. If docking is not feasible due to high sea state, the Glider can remain under tow until safer conditions prevail.

The operational timeline for the ROV Glider is shown in Figure 4.2.2-2.

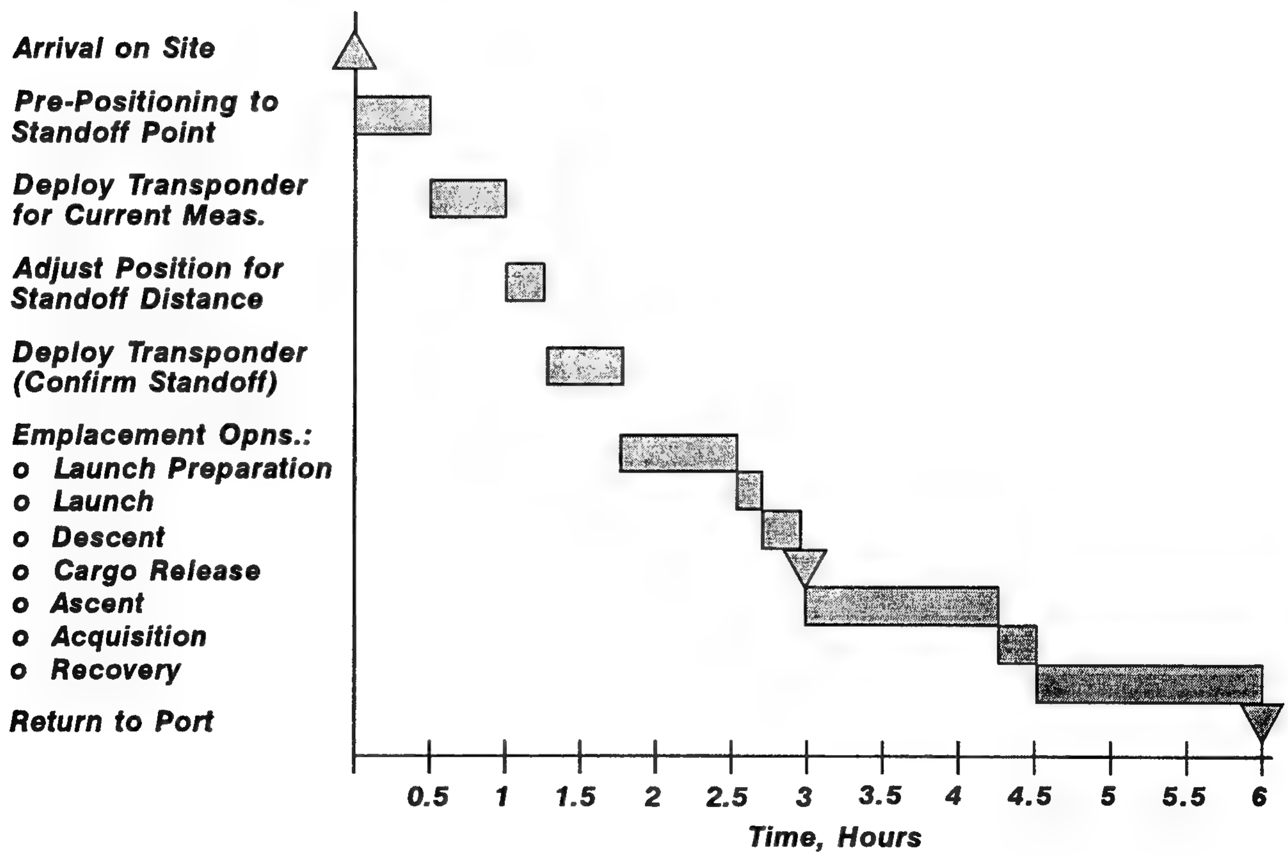

Figure 4.2.2-2 ROV Glider Operational Timeline

ROV Glider Key Technical Issues

- **Glider Stability:**

  Unique to the Glider is its change of buoyancy from negative to positive upon releasing its cargo while in forward motion. While the concept is viable, more research and empirical testing will be required to ascertain the vehicle and cargo dynamics at, during, and following release.

- **Acoustic Navigation:**

  In concept, the ROV Glider is to autonomously navigate to the exact drop location relying on acoustic telemetry to verify and/or correct its flight path. Noise, data speed and data integrity are known problems working with underwater acoustical telemetry. Noise is traditionally generated by a vessel's own propulsion system, but in this case it would be generated from flow noise around the Glider moving at approximately 11 m/s. Acoustical data transmission speed and integrity are also problems that autonomous underwater vehicles (AUVs) have been dealing with for several years. The development of the Glider concept would require some additional experimentation to verify that the use of acoustical navigation meets its reliability needs.

Other technical issues related to the ROV Glider are similar to the Surface Emplacement concept. These are:

- **Bag Survivability:**

  It is anticipated that the bags will reach terminal velocity in a less than 50 feet of free fall, based on the COE experiments. This indicates that the bag survivability issue is the same for the ROV Glider and Direct Descent Disk (with only 200 m of free fall) as for the Surface Emplacement concept (with over 6000 m of free fall). The issue of bag survivability upon landing on the seafloor is important for all three concepts utilizing bags.

- **Cargo Bay/Trap Door Design:**

  As with Surface Emplacement, trap door and cargo bay design of the ROV Glider is important to prevent bag tearing during release from the cargo cells.

- **Throw-Away Transponders:**

  Battery powered/multiple channel transponders will be required to assure that the bags are emplaced within the desired emplacement site monitoring area.

- **Geotextile Bags:**

  The bags used in the ROV Glider Concept to store the three waste streams are smaller in size, and therefore use more fabric, than those used for Surface Emplacement. The issue of selecting the appropriate type of bag material and verification that production rates can be met is critical.

4.2.3 DIRECT DESCENT DISK

The Direct Descent Disk concept is illustrated in Figures 4.2.3-1 and 4.2.3-2. Figure 4.2.3-1 displays five coupled Floater Modules, each carrying its own Disk. Similar to the ROV Glider, the Direct Descent Disk is configured into hexagonal cargo bays (Figure 4.2.3-2). A total of 169 cargo bays of 19 m^3 capacity each are arranged in a large hex array to produce an overall Disk diameter of 36.6 m. Flexible bags are used to contain the waste material in the cargo bays. When the Disk is fully loaded it is negatively buoyant. The floater module is then used to transport the Disk to the emplacement site. The Disks are positively buoyant once the cargo is released, and naturally float to the surface to be recovered by their floater modules. Additional features include the following:

- Louvered drag brakes enable the Disk to decelerate at approximately 100 m above the seafloor. Brake actuation will be timed with the ganged release of the cargo bay trap doors to impart a relative acceleration on the bags with respect to the Disk.

- Vortex shedding surfaces provide improved stability to the Disk, reducing both rotational instability and pitching instability.

The estimated negative displacement of the Direct Descent Disk is 2085 metric tons in seawater, fully loaded, and reflects the operational condition of being a free flooding, pressure-tolerant vessel for descending to abyssal depths. The net positive buoyancy of the Disk is approximately 107 metric tons, after release of the cargo, providing the means for the Disk to buoyantly return to the surface. Descent terminal velocity is approximately 6.7 m/s (21.9 ft/s), and ascent terminal velocity is approximately 1.6 m/s (5.3 ft/s), based upon a coefficient of drag of 1.17, and a Disk projected area of 772 m^2 (8300 ft^2). Note that if the trap doors remain open during ascent, the ascent terminal velocity would be approximately 2.2 m/s (7.2 ft/s). Upon activation of the louvered drag brakes, with simultaneous release of the bulk cargo, the Disk deceleration would occur over an approximate 3.5 second period, stopping its descent within a distance of approximately 7.3 m (24 ft).

The Floater Module provides an additional 4300 metric tons of displacement, or positive buoyancy, to that of the Direct Descent Disk. It is attached to the Disk at six points by ram-engaged detented latching assemblies of 3000 metric tons load capacity each. The integrated Floater Module/Direct Descent Disk configuration would have a fully loaded draft of approximately 4.9 m (16 ft), a beam of 41.5 m (136 ft) and a length of approximately 51.2 m (168 ft). Slots, located on the hull bottom, 4.9 m (18 ft) high by 37.8 m (124 ft) wide are provided on the port and starboard sides of the module to permit recovery of the Disk after the emplacement operation. The slot dimension height is based upon the need to provide clearance of approximately 1.5 m (5 ft) between that of the Floater Module underside and that of the surfaced Disk. The Floater Module is self-powered, uses four deployable thrusters, and provides the means to recover the Disk in the open ocean in sea state five conditions, by "driving over" the Disk, positioning itself to align the latching assemblies to that of the Disk attachment points, engaging and hoisting the Disk to a fully retracted position within the module, and subsequently returning to the host vessel, for return to port. Note that Floater Modules are manned during Disk release and recovery. They are unmanned during transit between port and the APWI site.

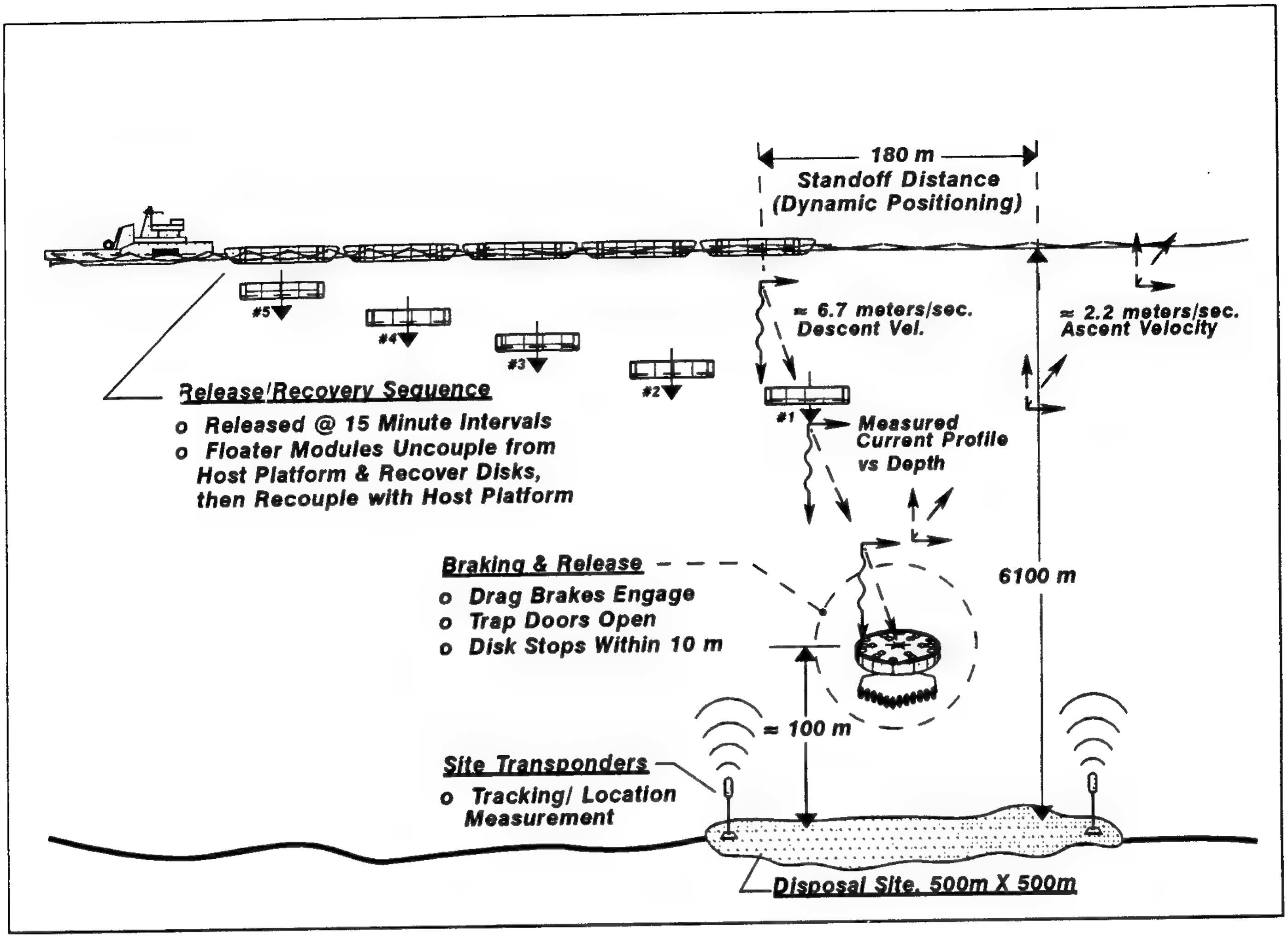

Figure 4.2.3-1 Direct Descent Disk Concept uses 5 ea. 5000 DWT Capacity Modular Elements to Descend to Abyssal Depths, Release Its Cargo, and Return to the Surface

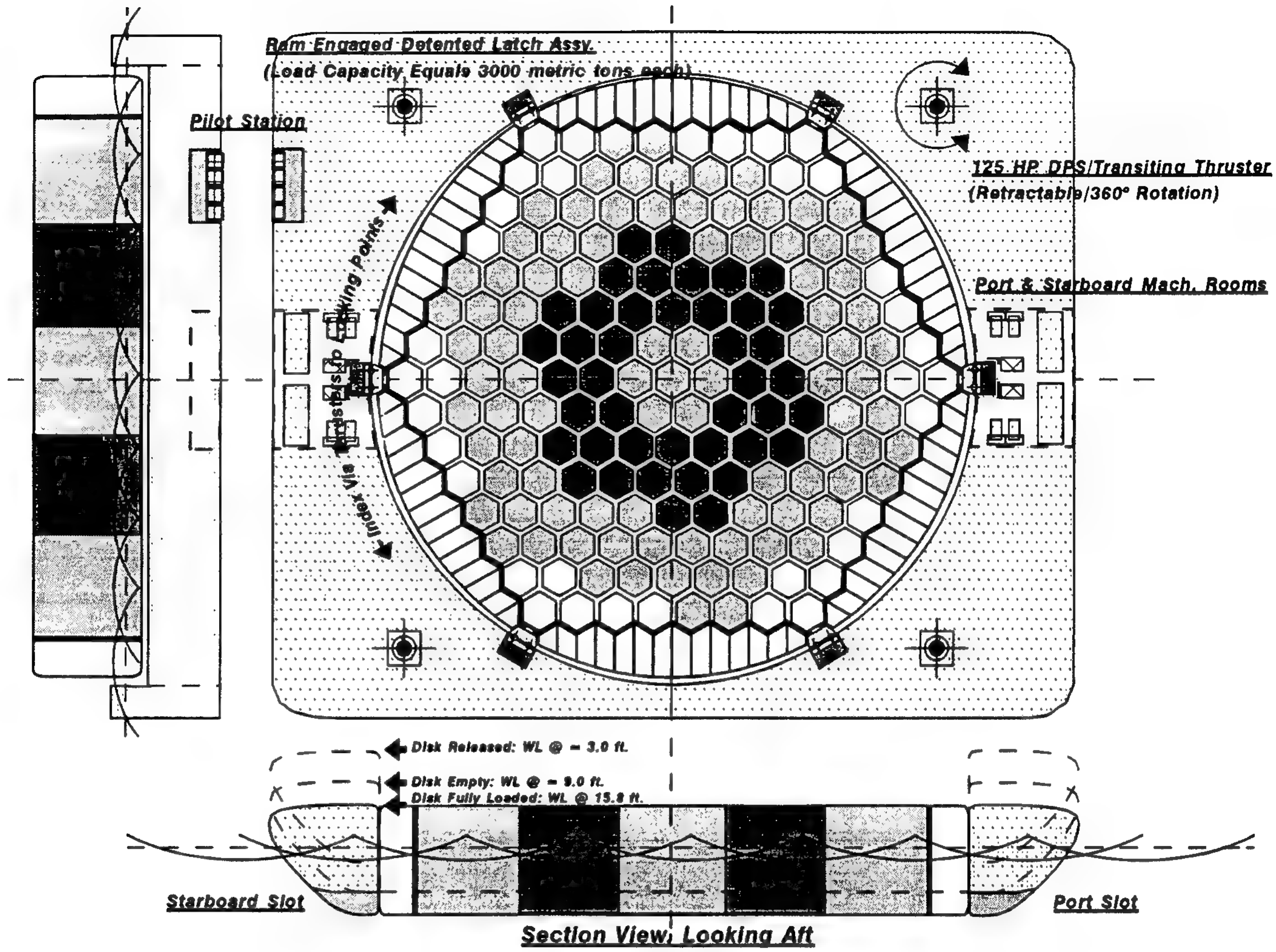

Figure 4.2.3-2 Direct Descent Disk Integrated with Floater Module.4300 Metric Ton Displacement Floater Module Configuration for Segmented ITB, Self-Propelled, Disk Recovery Via Driving Over the Surfaced Disk

Direct Descent Disk Operational Description

Release of the Direct Descent Disks at the isolation site location would occur with the following scenario of operation:

- The ITB transporter configuration, consisting of five Floater Modules, arrives on-site, identified by on-board navigation/global positioning system, and dynamically positions to a predefined standoff distance for release of the Direct Descent Disks. This standoff distance is based upon previously established knowledge of current conditions existing throughout the water column, such that the adjustment is made for drift due to current flow field over Disk free-fall descent. The free-fall descent velocity will be approximately 6.7 m/s. For an APWI site located at 6100 m depth, with average currents in the water column of 0.21 m/s (0.4 knots), the required standoff distance would be approximately 180 m.

- The ITB transporter interrogates previously deployed and located bottom mounted transponders to confirm its relative position with respect to the site, and the status of the bottom transponders in the site range. A deployable transponder is released, having a terminal velocity of 6.7 m/s. The transporter confirms that the transponder has landed within the targeted area. If not, adjustment is made to the vessels relative position, and a second transponder is released. The required time for the first (and any subsequent trial) is less than 16 minutes, before commencement of the next step.

- The ITB transporter initiates the sequential release of the five Direct Descent Disks at approximately 15 minute intervals, proceeding at approximately 3 knots speed of advance, on a track perpendicular to the prevailing current. The individual disks will be released at approximately 500 m intervals. The time and distance separation is established to assure that the possibility of collision between Disks is very low. The descent of the individual Disks, including ascent after release of the cargo, is tracked by the host platform using transponders operating on a unique frequency, and monitored using equipment similar to the Benthos DS-7000-16 Acoustic Signal Processing Deckset. The transponders would operate in a useable frequency range of 7 to 15 kHz, on 1 kHz increments, and would be matched to a high performance hull mounted transducer for deep water applications. The Deckset interrogates each Direct Descent Disk as it nears the seafloor and tracks it to its point of cargo release. This position is logged by vessel personnel and maintained in permanent record-keeping form, to comply with expected permitting requirements.

- The Direct Descent Disk initiates simultaneous activation of the drag brakes and release of the cargo cell trap doors at approximately 100 m above the seafloor. The bagged waste continues towards the seafloor at a velocity of approximately 5.3 m/s, as the Disk decelerates to zero velocity within a distance of approximately 10 m. The Disk then proceeds to ascend at a terminal velocity of approximately 1.6 m/s.

- Recovery operations commence once all disks have returned to the surface, with each of the Floater Modules performing the following sequence of operations:

  - Disengagement from the host platform, acquisition and tracking of the respective disk to the recovery location

  - Transiting at 3 to 5 knots to the disk location, and final positioning maneuvers for disk engagement

  - "Drive-over" capture of the disk, and alignment with latching assemblies by ballast adjustment

  - Latching engagement and de-ballasting, preparation for return to the host platform location

  - Sequential reengagement of the individual Floater Modules into the ITB configuration, and return to port

The operational timeline for the Direct Descent Disk concept is shown in Figure 4.2.3-3.

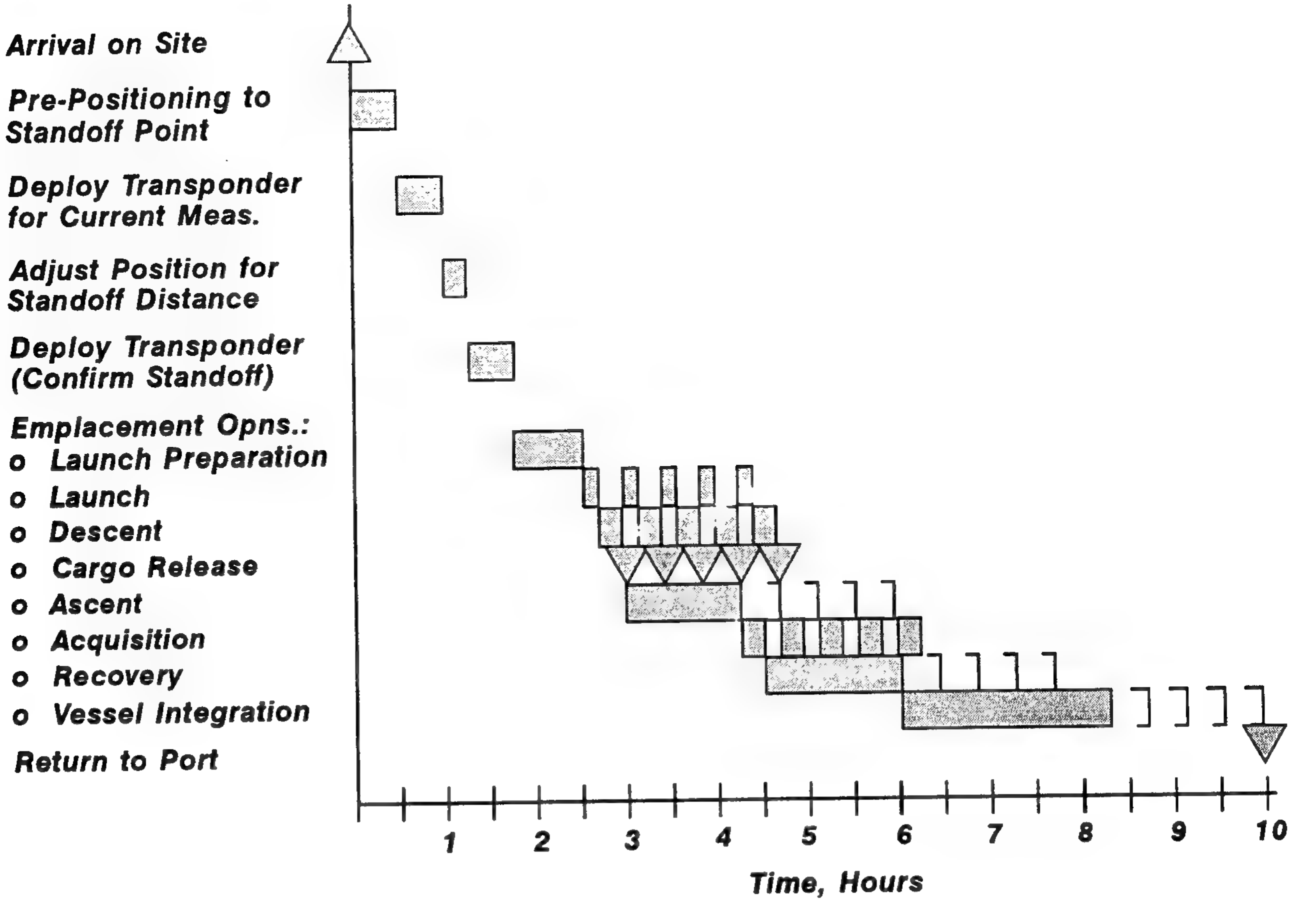

Figure 4.2.3-3 Direct Descent Disk Operational Timeline

Direct Descent Disk Key Technical Issues

- **Emplacement Accuracy:**

  The Disk concept is intended to descend in a nearly vertical path toward the seafloor. However, the probability or magnitude of the Disk to drift or skate off horizontally from its intended path is unknown at this time. This drift condition could be caused by loading variations such as inconsistent filling of cargo bays or variability in bulk specific gravity of the cargo. Computer modelling, simulation and/or physical models could be employed to quantify this characteristic.

- **Floater Module Operation:**

  The floater module concept provides enhanced flexibility over a conventional ship with perhaps a moon pool for launching and recovering Disks. However, this unique floater module feature does not come without its own set of issues. The response characteristics of a segmented/multi-connection string of barges in ITB configuration, under open ocean conditions needs to be assessed. Also, the floater/disk combination both loaded and empty must be assessed for its seaworthiness, as it is intended to be manned during emplacement operations. Recovery of the empty Disks by floater modules and recoupling of the floater modules with the tug, at sea, is an issue that warrants considerable analysis.

Other technical issues related to the Direct Descent Disk are similar to the Surface Emplacement and ROV Glider concepts. These are:

- Bag Survivability:

  This is exactly the same issue as with Surface Emplacement and the ROV Glider.

- Cargo Bay/Trap Door Design:

  As with Surface Emplacement and the ROV Glider, trap door and cargo bay design are important to prevent bag tearing during emplacement. Also trap door reliability is extremely important since 165 out of 169 cells must properly release their cargo for the Disk to resurface.

- Throw-Away Transponders:

  Battery powered/multiple channel transponders will be required to assure that the bags are emplaced within the desired isolation site monitoring area.

- Geotextile Bags:

  The cargo cells in the Direct Descent Disk are the smallest of all concepts that use bags, and therefore this concept uses the most bag fabric material. The issue of selecting the appropriate type of bag material and verification that production rates can be met is critical.

4.2.4 PIPE RISER

The Pipe Riser concept is illustrated in Figure 4.2.4-1. The Pipe Riser utilizes the principle of gravity flow for the transport of up to 2400 metric tons/hr per discharge line of bulk waste into a designated emplacement site approximately 500 m X 500 m. Utilization of gravity flow results in minimizing the size of the pumping system, estimated in excess of 1200 kw (16,000 HP) that would otherwise be required for moving the large volume of slurryized bulk waste through a Riser piping system of 6500 m (21,000 ft). The gravity flow design capability of 2400 metric tons/hr per line is based upon employment of 1.37 m (54 in) outside diameter (OD) X 1.26 m (49.8 in) inside diameter (ID) Driscopipe, a high density polyethylene (HDPE) piping system presently utilized for the pumping of a variety of slurry materials. Gravity flow conditions are initiated by introducing the bulk waste slurry fluid, having a specific gravity greater than seawater into the top of the Riser, thereby creating a higher static head within the riser discharge line than that of the surrounding seawater. This static head provides the potential energy to raise the discharge flow volume from "zero" to the limit flow volume. The limit flow volume is achieved when the net line losses due to flow equals that of the static head. A diffuser provides means to keep discharge flow velocities to less than 1.5 m/s (5.0 ft/s).

Transporters, providing approximately 25,000 DWT bulk cargo, arrive from various ports of opportunity along the Atlantic, Gulf and Pacific coasts, after a transit of 1060 km (570 nmi) average distance. The bulk cargo will generally have a high solids content, or bulk specific gravity, in excess of that required to establish safe gravity flow operating conditions, and will require dilution with slurry water to establish the desired bulk specific gravity. This dilution seawater is provided from depths of approximately 760 m, mixed with the bulk waste being off-loaded from the transporter, and is used to "charge" the discharge lines. Charging of the lines requires approximately 30 minutes to establish the desired specific gravity along the entire line length and achieve full gravity flow conditions.

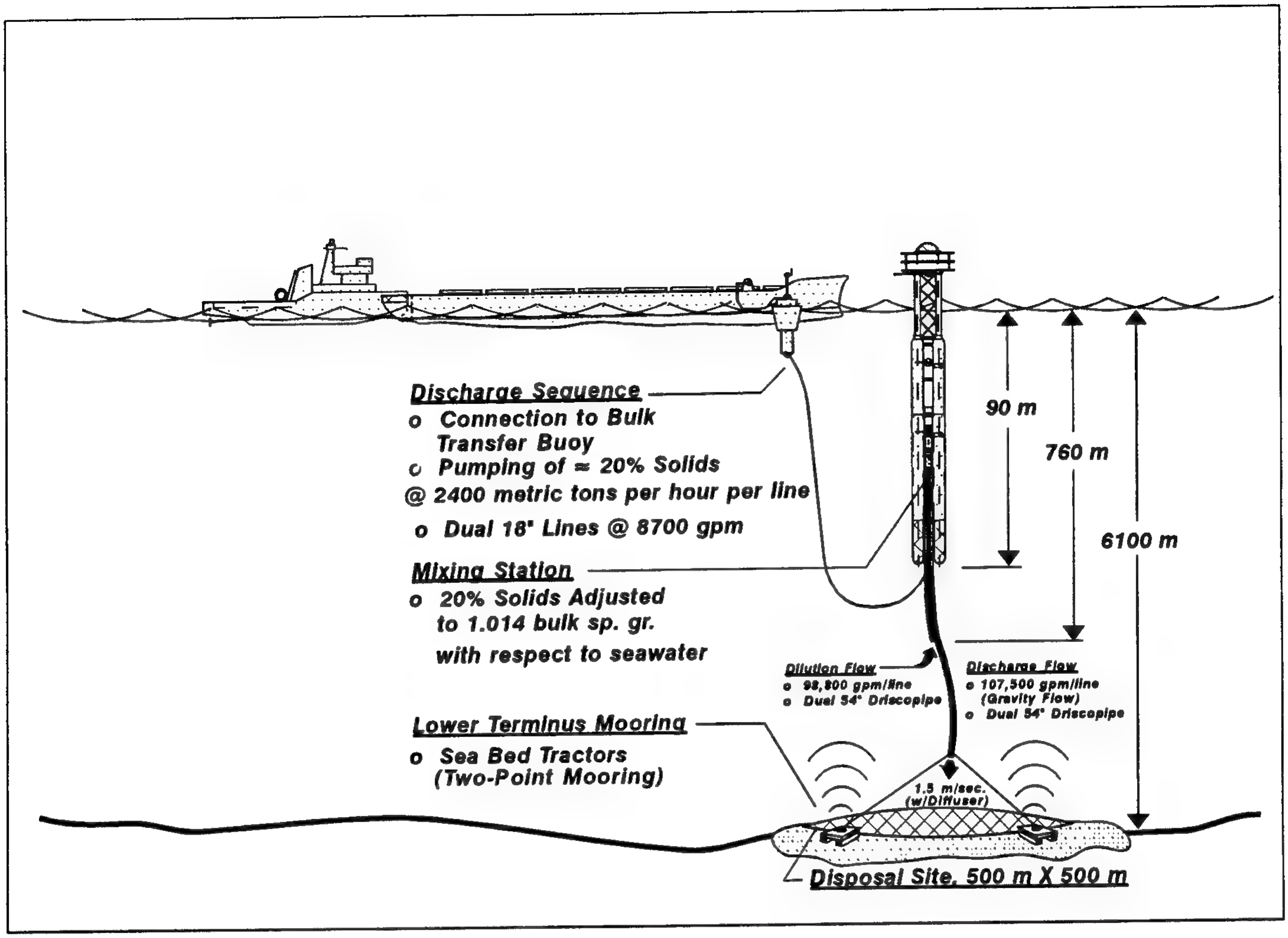

Figure 4.2.4-1 Pipe Riser Concept Employs a Dynamically Positioned Spar Buoy Assembly with Pipe Riser System to Emplace 4800 Metric Tons/Hour Slurryized Bulk Waste

The Pipe Riser consists of three major subassemblies:

- The Pipe Riser Assembly consists of two 1.4 m (54 in) OD suction (or dilution) lines approximately 760 m in length and two 1.4 m (54 in) OD discharge lines approximately 6500 m in length. The discharge line length is dictated by the depth of the APWI site location and the prevailing current conditions existing within the intervening water column. A fifth line 0.45 m (18 in) OD approximately 70 m in length is provided at the upper end of the Pipe Riser to provide a pipeline connection of discharge flow from "off-loading" transporters to a mixing chamber located atop the Riser assembly. The Pipe Riser consists of 15.2 m (50 ft) modules designed for on-site final integration into the pipe riser configuration, approximately 6500 m in length.

- A Spar Buoy Upper and Lower Terminus Assembly, with dynamic positioning capability, to maintain the relative position of the upper section of the Pipe Riser Assembly directly above that of the lower section of the Pipe Riser Assembly. The Lower Terminus of the riser is "moored" to the center of the designated APWI site, with provision to control the "moored" position within a 10 km x 10 km abyssal site, by use of motorized seabed tractors (mobile gravity anchors). The structural connective element between the Upper and the Lower Terminus is the Pipe Riser Assembly, which acts as the "mooring" line for the Spar Buoy, with 2700 kN (600,000 lb) line tension capability. The Spar Buoy Upper Terminus Assembly is approximately 10,000 metric tons displacement, and provides features for +/- 37 m (120 ft) motion compensation of the Pipe Riser Assembly. The Spar Buoy provides equivalent (or better) stability characteristics versus that of unmoored dynamically positioned semisubmersible platforms and provides capability for continuous operation in sea state 5 conditions. Additionally, as with unmoored semisubmersible platforms, it is capable of surviving sea state 8 conditions. The Spar Buoy is designed to be unmanned during periods when transport vessels are not on-site, maintaining its station-keeping functions autonomously. Communication links provide human intervention/ monitoring capability from shore-based control sites.

- Dual motorized seabed tractors (mobile gravity anchors), with equivalent clump weight of greater than 145 metric tons each, provide capability to adjust the moored position of the Pipe Riser. This adjustment in moored position is desirable to facilitate the transfer of the emplacement operations to successive 500 m X 500 m sites within the designated 10 km X 10 km site location. This transfer would occur after approximately 4.5 million metric tons of bulk waste have been deposited in a single mound of 500 m diameter, 15.5 m high. Transfer of isolation operations could occur at three month intervals, depending on the total waste volume arriving at the APWI site. The relocation to an adjacent emplacement site would require from four to eight hours to accomplish. The submerged weight of the seabed tractors /gravity anchors is dictated by the requirement to provide tractive effort sufficient to overcome induced drag load force components acting on the Pipe Riser at its Lower Terminus.

Pipe Riser Operational Description

The Riser control system oversees and/or controls all aspects of the emplacement operation. This includes pump control and power supply, valve control (not including Riser safety valves which are spring or pilot actuated), Riser motion compensation system and tensioner equipment. The control system provides all command and data processing for the Riser safety and status instrumentation.

There are two active control systems during the emplacement operation. The primary system resides within the surface platform and has full control of all Riser control functions. A fully redundant system resides on the waste transport vessel with personnel overseeing operations with capability of overriding any command. The control system monitors waste off-loading rates and density. Based on these parameters, the sea water

intake flow rates are varied to provide a net slurry bulk specific gravity of approximately 1.014 (with respect to sea water). Typically, the waste is diluted in-line so that it is emplaced without delay and need for any on-site storage. As the slurry proceeds down the Riser, the flow rate, pressure, and density are measured at approximately 300 m (1000 ft) intervals. Assuming a flow rate of 5.5 m/s (18 fps), this allows flow readings of the same mass at approximately every 56 seconds. If conditions of high pressure, high density or high flow velocity are measured, the water intake rate is increased and/or the waste off-loading rate is decreased until the pressure, density, or flow rate reading is within bounds.

The primary control system is located within watertight compartments at the top of the Riser assembly. It includes dual 4200 kw primary power generation, a 1500 kw power source for suction pumps, 25 kw-h uninterruptable power supply, and dual 250 kw power sources for related auxiliary systems (trim and ballast transfer pumps; fuel transfer; bilge, etc.). Further redundancy in emergency power generation might also be provided by a 1 to 5 kw solar cell system for powering of emergency systems/warning beacons/alarms, etc. Most control functions are performed during emplacement operations, which are expected to be occurring 65% to 90% of the time, based upon sea state conditions impact on operational availability for the specific isolation site. During non-emplacement periods, the system is in a "low power" mode with only thrusters and instrumentation operating.

An operating scenario for unloading operations is described as follows:

- Bulk waste transporter arrives on-site and positions to maintain heading into the wind alongside the transfer buoy. Boom crane lifts transfer buoy line pendent to connect to discharge line(s) from the individual cargo bays. Vessel maintains station-keeping with respect to both the transfer buoy and the Spar Buoy, using its dynamic positioning thrusters. Line connection integrity is checked prior to next step.

- Vessel crew powers up Spar Buoy dilution pump(s), while simultaneously powering up the slurry transfer pumps, thereby filling the mixing chamber. The proportion of bulk slurry to dilution seawater is adjusted to realize a mixing chamber bulk specific gravity of <1.014 (with respect to seawater). Once the mixing chamber is filled to approximately 90% capacity, the isolation valve to the discharge line(s) is slowly opened, and buildup in discharge flow volume is initiated over the next 20+ minutes.

- Transport vessel off-loading proceeds at the rate of approximately 2400 metric tons/hr if using a single discharge line, or approximately 4800 metric tons/hr for both. Assuming 4800 metric tons/hr, the vessel could be unloaded in approximately 5.2 hours.

- Vessel crew powers down the Spar Buoy dilution pump(s), disconnects from the transfer buoy pendent line, and prepares for return to port.

The operational timeline for the Pipe Riser concept is shown in Figure 4.2.4-2.

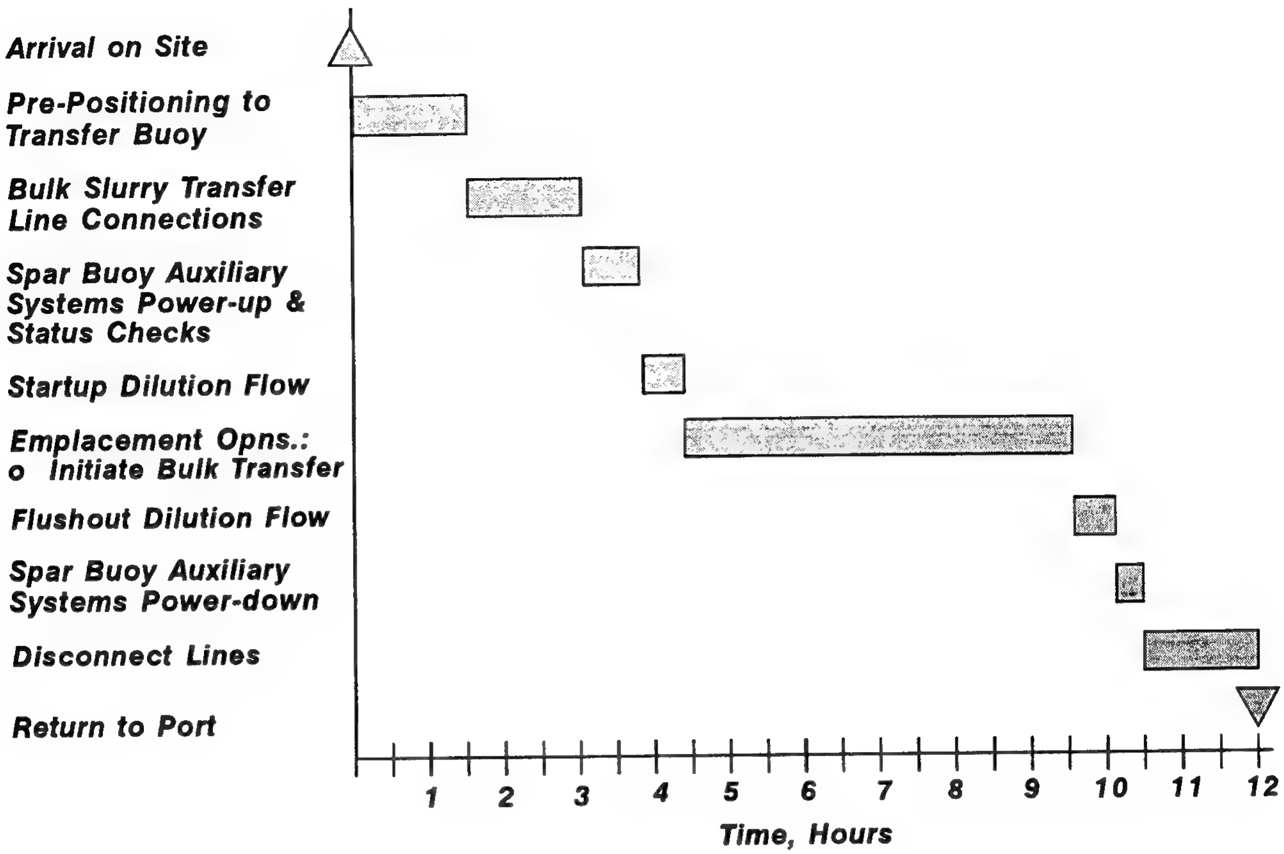

Figure 4.2.4-2 Pipe Riser Operational Timeline

Pipe Riser Key Technical Issues

The Pipe Riser concept is comprised of a number of elements, all of which present formidable technical and operational challenges. Comparison of the system scale, versus that of previous similar systems, indicates a 6 to 40 times increase in size. Indications are very high, based upon the preliminary concept definition provided, that potentially catastrophic failure modes will exist. Capability to provide the necessary reliability to mitigate these failure modes will only be realized by use of critical component redundancy. Additionally, incorporation of "large" design factors of safety will be required vis-a-vis operating conditions (to minimize operational stresses) in order to achieve the minimum desired level of component reliability. Finally, employment of system health monitoring techniques to anticipate incipient failures, will be mandatory for assuring the operational availability of the unmanned system. The Pipe Riser control system must be capable of establishing failsafe shutdown conditions autonomously, as capability to maintain the system is severely limited. This limitation is due to the open ocean location and the time required to transport repair personnel and spare parts. The use of scheduled maintenance will therefore be critical in the establishment of overall system reliability, by providing capability to fix "potential" problems before they become major problems.

The Pipe Riser presents unique problems, versus the other APWI concepts, with respect to scalability. Building a scale model doesn't translate, when one considers the water column dimension versus that of the associated hardware sizes. The designer must rely on simulation/modeling tools to determine the relevant loading response

characteristics of specific elements. These tools must rely on the accuracy of the modeling parameters, and be applicable to multiple degrees of freedom response evaluations. Technical issues expected to be resolved during a preliminary design phase are as follows:

- Motion compensation of +/- 37 m (120 ft.) at approximately 60% loads will have to be accomplished. This is approximately six times the travel distance of existing systems such as Vetco MC400-20-D, used for drillstring motion compensation.

  Dynamic simulation of the system, to assess response characteristics versus sea state loading conditions, will have to be performed. Results of the simulation runs will dictate the compensation to be considered for use in the Pipe Riser system.

- Slurry dilution/mixing and associated control system evaluation should be modeled using a simulation language similar to CSSL-IV. Performance evaluations should be conducted for all anticipated operational conditions. Optimization of the associated control/feedback strategy would be established by a process of iteration.

- The suction pumping system requires that dual 850 HP pumps be operated continuously at a working depth of 760 m to provide approximately 98,800 gpm discharge flow. Employment of pressure-compensated housings for the electric drive motors, with the associated pumps, is the desired approach, with the pump impeller shaft using a pressure-compensated hydrostatic suspension system and conventional Sealol shaft seals. Undersea intervention features must be established to facilitate maintenance capability.

- Failsafe Modes/Control System Redundancy must be thoroughly analyzed to proceed with this concept. Deployment and long term reliability are two critical issues.

- Seafloor tractor's (mobile gravity anchor) performance capability rests primarily with the emplacement site sediment properties. The design of the seafloor tractor's load bearing area versus weight in seawater and selection of tracked versus screw drive is contingent upon completion of a detailed site survey. The seafloor tractor's scalability, which is on the order of 50 times larger than conventional tractors, is a major issue. Deployment and long term reliability are two critical issues.

4.2.5 TETHERED CONTAINER

The Tethered Container concept was analyzed and determined to be unacceptable from both a production rate capability and because of handling system problems. The following concept description presents the concept and defines the technical problems. The Tethered Container Concept is shown in Figure 4.2.5-1 and employs a waste container that is lowered by a winch and tether to the seafloor from the surface support vessel and recovered after releasing its contents. The main elements of the concept are the waste container, tether, handling system, and the vessel.

The maximized system yields 250 metric tons of waste material emplaced every 1.05 hours or (240 metric tons/hr) at abyssal depths.

The concept consists of a 190 m^3 (250 yd^3) capacity container that weighs over approximately 100 metric tons in sea water when filled. The container is made of aluminum and is 4.3 m (14 ft) in diameter and 6.6 m (21.5 ft) in height. It is designed to carry materials having a bulk specific gravity up to 1.25. The container is filled with waste material by an auger or conveyor through a flanged interface. The estimated time for loading the container is 13 minutes, using dual 1200 metric tons/hr conveyors.

Ship motion in the open sea, especially motion caused by wave action, makes handling the container difficult. The dynamic input results in very high loads when handling such a large mass.

The handling system is designed to minimize the dynamic inputs, thereby reducing the apparent loads on the tether and container. The handling system consists of a docking cage, a heave compensation system, and a winch which operates through a moonpool in the support vessel.

The most effective means of reducing the effect of ship motion on the handling system and thus the container is to operate the system through a moonpool. The moonpool reduces the effects of wave action during operation, except for heave. The moonpool design for this system is critical for several reasons. First of all, the size of the moonpool in the support vessel (approximately 10 m X 10 m) is very large to accommodate the waste container. The vessel will be significantly modified and strengthened to incorporate a moonpool of this size. Secondly, because of the moonpool's large area, the vessel will have deployable skirting around the moonpool's opening that extends down from the bottom of the vessel. This skirting will help dampen wave action inside the vessel.

The waste container is captured in a retractable docking cage during the loading, launch, release and retrieval. The docking cage travels vertically on a track through the moonpool for filling, release, and recapture of the container below the air/water interface. The docking cage will protect the perimeter of the moonpool from damage due to angular motion of the vessel. The docking cage must react to the side loads imparted on the container as the vessel reacts to the seas. The cage requires a larger moonpool but makes the launch and recovery of the large container safer.

The winching assembly would require approximately 4500 HP at 85% efficiency. The winch drum barrel size would be approximately 5.1 m (16.7 ft) in diameter to provide a d/D (diameter of tether/diameter of winch drum barrel) of 40:1 to minimize tether induced stresses due to bending. Assuming an 8 wrap configuration, the flange-to-flange spacing would be approximately 6.1 m (20.0 ft). A levelwind assembly would be required to maintain uniformity in the tether layup onto the winch drum.

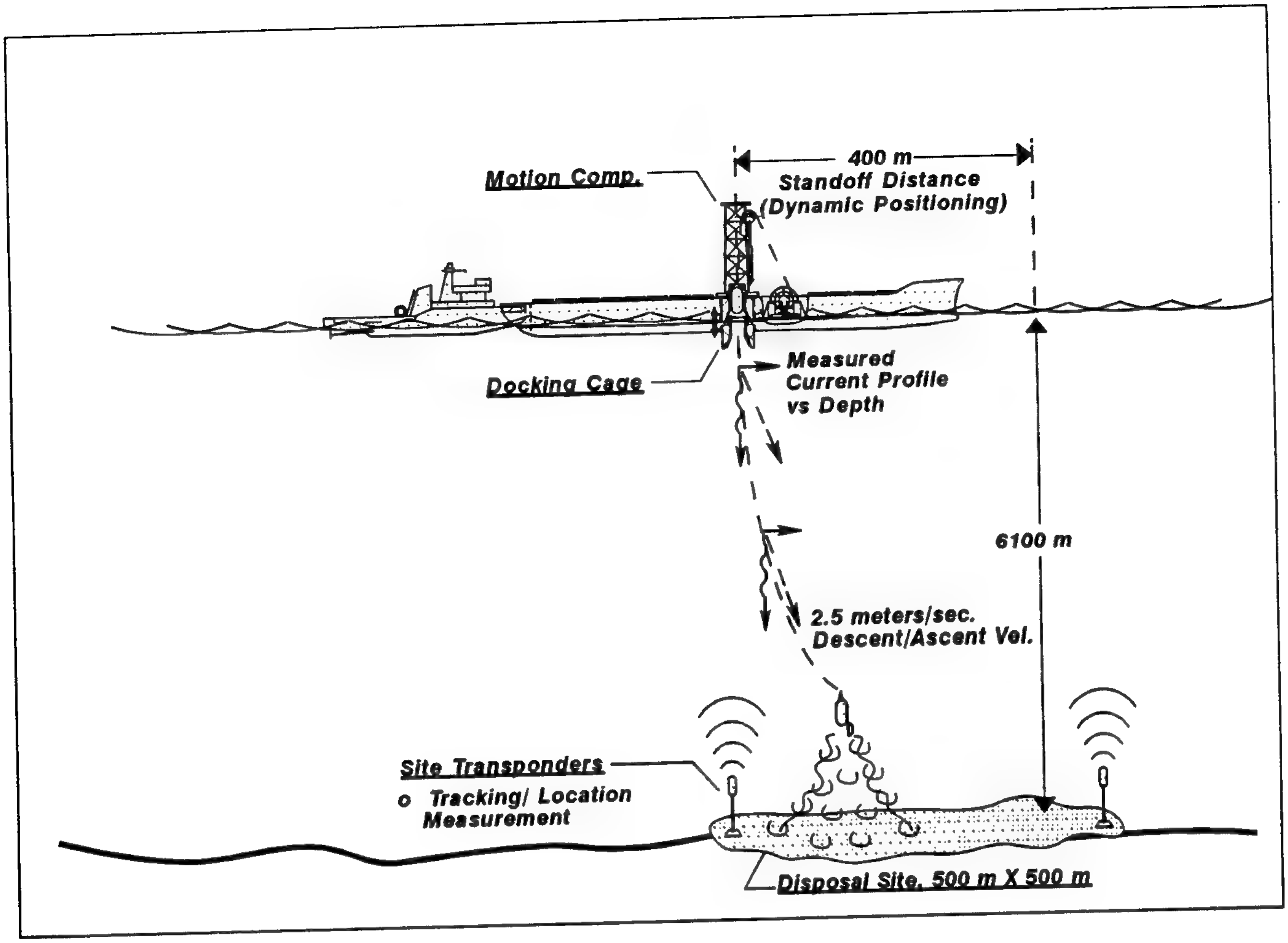

Figure 4.2.5-1 Tethered Container Concept Uses a 190 m^3 Capacity Container for Deposit of 240 Metric Tons/Hour Bulk Waste into APWI Disposal Site

The heave compensation system prevents the rope from being impacted by abrupt vertical acceleration (snap loads). A hydraulically tensioned head sheave located above the moonpool dampens heave. The hydraulic cylinders maintain a preset pressure. When the ship heaves upwards, the increased pressure is relieved and the sheave maintains position. Conversely, as the ship heaves downwards the pressure to the cylinders is increased to the preset pressure. The heave compensation system will mitigate the otherwise expected heave accelerations which could be as great as 1.3 g (17.7 m/s^2 or 58 ft/s^2) in sea state 5.

Based upon a maximum allowable acceleration of 0.085 m/s^2 (0.28 ft/s^2) due to changes in tether deployment or retrieval speed, the minimum induced change to the tether line tension would be approximately +/- 42 kN (9,400 lb). Accounting for the added mass of "entrained water," which is approximately equal to that of the container displacement volume, and including the mass of the tether at 78 metric tons, yields a line tension change of +/- 83 kN (18,450 lb). The magnitude of the change in tether line tension is directly proportional to the acceleration level. Noting that the heave compensation system must be capable of mitigating expected heave acceleration levels as great as 1.3 g (17.7 m/s^2 or 58 ft/s^2) in sea state 5, we see that sea state effects generate approximately 200 times the acceleration levels of that of normal winching operation. The heave compensation system must therefore have capability to isolate approximately 99.5% of the induced heave acceleration levels from that of the tether management system, if "constant tension" values are to be maintained at +/- 10% of the desired setpoint. This value of +/- 10% is at the upper limit of achievable tension control capability for heave compensation systems. In the event of failure of this system, or in situations of degraded operational performance, the tension fluctuations could be expected to rapidly exceed that of the tether breaking strength.

The tether selected for the concept is a synthetic line. Synthetic line is more easily handled than the alternatives and offers a great benefit of a low in-water weight. Synthetic line has a good strength to weight ratio as compared to other options and is resistant to the environmental degradation. The synthetic line chosen is an aramid-fibered line. This aramid-fibered line has a 8.1 MN (1.8 million lb) break strength in a virgin, unspliced condition. The line is 0.13 m (5 in) in diameter and requires the use of 5.1 m (16.7 ft) minimum diameter sheaves. The 0.13 m (5 in) diameter line has a block creel of 300 m (1000 ft), which is the maximum strand length that can be wound on a single rope-making machine's bobbin. Therefore, a continuous 22,000 ft section of the 0.13 m (5 in) diameter, 7 X 19 line will have no less than 22 splices per strand times 7 strands. The line will be derated at least by 10% for the splices. The recommended working load of the line should include at least a factor of safety of 7 for heavy use. Again derating the line for extended fatigue life, the recommended working load of the line is 1.05 MN (230,000 lb).

Aramid-fibered line demonstrates elastic properties similar to wire rope. The line will not tolerate any impact or shock loads. If the line is stopped abruptly or if it is otherwise shock loaded, it will part. This sensitivity to impact loading drives the handling system design.

The tethered concept is very likely to fail by premature fatigue because of the natural frequency of the line. The natural frequency of the tether is in the same range as expected ship motion inputs. The cross current vortex shedding also produces frequencies in the same range. Both of these conditions can excite the rope and lead to strumming or other larger oscillations in the rope. The excited rope will fail due to fatigue if these conditions are present.

Finally, the primary downfall of the tethered concept is its low emplacement rate caused by limitations on existing diameters of synthetic line. There are many other limiting factors; however the tether represents the driving force which negatively impacts the concept. The tether characteristics drive the entire concept design and limit the system capacity. The maximized system yields 250 metric tons of waste material emplaced every 1.05 hr, or 240 metric tons/hr, at abyssal depths. This capacity falls far short of the economic minimum baseline of 4800 metric tons/hr emplaced. As a result, the tethered container does not qualify as a viable concept of APWI.

4.3 RELIABILITY ANALYSIS

Two independent reliability analyses were performed for the Abyssal Plains Waste Isolation Project (APWI) for the purposes of identifying and assessing reliability risks associated with the APWI mission. In addition, the risk indices of the four concepts under evaluation to emplace waste stream products at abyssal seafloor sites were compared.

The APWI mission is to transfer efficiently and safely, dredged material, sewage sludge, and fly ash from a port or harbor to a specified APWI site without waste loss in the intervening water column.

The ultimate objective of the reliability analyses is to provide data as input to the systems level analysis evaluating each concept for feasibility and to assist in selecting the best overall concept(s) for further evaluation.

The two analysis approaches are:

a) Fault Tree Analysis
b) Failure Modes, Effects, and Criticality Analysis (FMECA)

The four APWI concepts analyzed are:

a) Surface Emplacement
b) Direct Descent Disk
c) ROV Glider
d) Pipe Riser

In addition, analyses were performed for waste handling at port and transportation to the APWI site. Early analysis effort indicated that there was no appreciable reliability risk difference for these mission segments between the four emplacement concepts.

Fault Tree Analysis

Fault Tree Analysis (FTA) is a graphical design analysis technique used extensively in Reliability, Safety, and Maintainability Engineering. It starts by identifying a top level undesired event (e.g., a failure mode or a safety hazard) and how the top event can be caused by individual or lower level events or failures.

Fault trees have been generated for all APWI mission scenario and segment elements. These fault trees are included in Section 6.0 of the Technical Assessment Report. The more complex the element, the more realistic are the potential causes of failure. No major risks have been identified that can not be mitigated either through added redundancy or improved operating procedures, e.g., shut down operations in bad weather to secure equipment and avoid damage or waste spillage.

Although the risks in the fault tree were not "quantified" by either severity or probability of occurrence, the Pipe Riser approach presents more reliability related risks than any other approach. The remainder appear to have equivalent risk. Also note that the risks of most concern in transporting the waste stream products from shore to the isolation site are primarily related to external conditions and not the hardware involved.

Failure modes, Effects, and Criticality Analysis

The approach to generating the APWI FMECA was to first list all major components and mission functions of interest. Then, by examining concept block diagrams and through working group "brain-storming" sessions, the

function of each was identified. Next, all reasonably possible failure modes of components or functions and their effects on the mission and environment were analyzed.

Assigning severity categories and probabilities of failure were the final steps in the APWI FMECA process. These were assigned for each failure mode and significant causes.

Each failure mode was assigned a qualitative probability value from the probability of occurrence (PO) levels shown in Table 4.3-1. Each failure cause and effect was subjectively assigned a severity class (SC) from the scale shown in Table 4.3-2. Taken together the PO and SC determine each element's criticality or risk index.

Table 4.3-1 Qualitative Probabilities of Occurrence

Level	Definition
Level A - Frequent	A high probability of occurrence during the item's operating lifetime.
Level B - Reasonable Probable	A moderate probability of occurrence during the item's operating lifetime.
Level C - Occasional	An occasional probability of occurrence during the item's operating lifetime.
Level D - Remote	An unlikely probability of occurrence during the item's operating lifetime.
Level E - Extremely Unlikely	A failure whose probability of occurrence is essentially zero during the item's operating lifetime.

Table 4.3-2 Severity Class

Level	Definition
Category I - Catastrophic	A failure that may cause death, a major waste exposure, major waste spill, or loss of major portions of the APWI concept.
Category II - Critical	A failure that may cause severe injury, significant personnel exposure or intervening water column waste loss, major system or facility/component damage that will result in significant system downtime.
Category III - Marginal	A failure that may cause minor injury, minimal personnel exposure or intervening water column waste loss, minor component or facility/component damage that will result in system downtime.
Category IV - Minor	A failure that is not serious enough to cause injury, waste exposure, or equipment damage, but will result in substandard system operation. Repair can be scheduled at normal scheduled maintenance intervals.
Category V - No Effect	A failure that has no impact on system operation and does not result in unscheduled downtime.

To compare risk levels of alternate approaches, numerical weightings were assigned to both severity class and probability as in Table 4.3-3, multiplied for each major failure/failure cause to obtain a risk index, and summed for each configuration approach and mission segment.

Table 4.3-3 Risk Weighting Factors

Severity Class	Weighting	Probabilities of Occurrence
Cat I	4	A
Cat II	3	B
Cat III	2	C
Cat IV	1	D
Cat V	0	E

The results of the calculated weighted risk indexes are as follows:

a) Waste Stream Product Handling @ Port	29
b) Transit to Site	14
c) Pipe Riser	147
d) Surface Emplacement	34
e) Direct Descent Disk	95
f) ROV Glider	101

These scores allow a comparison of relative risk between the concepts and are not intended to represent absolute risk values.

This risk ranking indicates that the Surface Emplacement concept offers the least operational risk, while the Pipe Riser is clearly the concept with the highest risk. The ROV Glider and the Direct Descent Disk concepts are basically rank equal. Also, the risk due to loading at port and transiting is low compared to the emplacement risks.

5.0 ECONOMICS ANALYSIS OVERVIEW

Four Abyssal Plains Waste Isolation concepts were identified during the technical assessment phase of this study that provide technically feasible approaches for isolation of contaminated dredged materials, sewage sludge, and municipal incinerator fly ash.

In order to determine the emplacement costs for each of these concepts, nonrecurring capital costs and annual operating costs were estimated.

The results of the cost analysis is summarized below in Table 5.0-1. For this analysis, operational availability is assumed to be 100%; however, eight hours per emplacement trip is allocated for maintenance.

Table 5.0-1 Summary of Emplacement Costs

Concept	Cost per metric ton of Sewage Sludge and Fly Ash	Cost per Cubic Yard of Dredged Material
Surface Emplacement	$15.00	$12.00
ROV Glider	$20.00	$16.00
Direct Descent Disk	$24.00	$20.00
Pipe Riser	$18.00	$15.00

Comparison of the annual emplacement costs per amount of material emplaced is surprisingly similar for all of the concepts, and indicates that, regardless of the concept, the cost/ton is within $10/ton for sewage sludge and fly ash, and $10/cubic yard for dredged material. The similarity in costs between concepts is dominated by two factors:

(1) The volume of emplaced waste is so large that variances in capital costs have little effect on the price of isolation per ton of material emplaced. For every $25 million increment in capital cost, the effect on emplacement cost is less than $2.00/metric ton. For example, the annual cost impact of $25 million dollars is $4.23 million/yr (amortized over eight years, at 7.25%). This impact on Surface Emplacement would then be: $4.23 million/yr / 2.38 million metric tons/yr = $1.78/metric ton.

(2) The operating costs for each of the systems are basically the same.

Another significant result is that the disposable bag, where used, accounts for an average 20% of the emplacement cost. For example, the ROV Glider's Total Annual Cost is $45 million with annual disposal bag cost of $7.85 million, or 17% of its Total Annual Cost. In any commercialized system with a significant single cost driver, such as the bag, efforts would be spent on lowering this specific cost. Therefore, in full scale operations, the bag cost would be reduced either through design changes or manufacturing economies of scale.

5.1 CAPITAL COSTS

Capital costs are those expenses which will not be repeated for the life of the system. These costs, for a new build, include:

- Engineering Design (but not including technology development in this analysis),
- Shipyard Production Engineering Costs,
- Material Acquisition,
- Shipyard Manufacturing Manhours,
- Builder's Trial, Certificate of Fitness, and Classification, and
- Port Facilities Cost.

The discussion of each of these costs are included in Section 3.1 of the Economic Viability Report. As an example, the ROV Glider Capital Costs is included below as Table 5.1-1. Other concept's capital costs contain the same categories.

Table 5.1-1 ROV Glider Capital Costs

Concept: PIPE RISER - CAPITAL COSTS

Category	Quantity (R=ROV, L=Launcher)	Riser (Millions $)	S. Buoy (Millions $)	Total (Millions $)
1. Design Cost	R = 16,500MH X $60.00/MH SB = 16,500MH X $60.00/MH	0.99	0.99	1.98
2. Shipyard Production Engineering Cost Engineering Manhours (Self-Powered or SP)	n/a	0.00	0.00	0.00
Engineering Manhours (Unmanned ITB or Other)	R = 16,500MH X $33.60/MH SB = 50,000MH X 33.60/MH	0.55	1.68	2.23
3. Material Acquisition Cost Steel	SB = 2500T X $1000/T	0.00	2.50	2.50
Driscopipe	R = 3400T X $3060/T	10.40	0.00	10.40
Concrete or Gel Ballast	sb = 2500T X $100/T	0.00	0.25	0.25
Propulsion & Electric Plant	SB = 500T X $5500/T	0.00	2.75	2.75
Electronic Subsystems	SB = 1 SYS X $.45M/SYS	0.00	0.45	0.45
Fluid Systems	SB = 50T X $2500/T	0.00	0.13	0.13
Remainder of Outfit	R = 340T X $3000/T SB = 300T X $3000/T	1.02	0.90	1.92
4. Shipyard Manufacturing Cost Structural	R = 340T X 75MH/T X $33.60/MH SB = 2500T X 75MH/T X $33.60/MH	0.86	6.30	7.16
Machinery Installation	SB = 500T X 200MH/T X $33.60/MH	0.00	3.36	3.36
Fluid Systems Installation	SB = 50T X 250MH/T X $33.60/MH	0.00	0.42	0.42
Remainder of Outfit	R = 340T X 150MH/T X $33.60/MH SB = 300T X 150MH/T X $33.60MH	1.71	1.51	3.22
5. On-site assembly Employs 18 people 12 hr shift, 24 hr/day @ $55.00/hr	Daily Operational Cost Labor: R = $23,760/day X 20 days SB = $23,760/day X 20 days Derrick Barge lease @ $200,000/day X 40 days	0.48 4.00	0.48 4.00	0.96 8.00
	Capital Cost Subtotal:	20.01	25.72	45.73
	Total Capital Cost with Typical Shipyard Profit:	22.01	28.29	50.30

T = Metric Ton (Mg)

5.2 ANNUAL COSTS

Annual costs are the yearly operating costs for an APWI system and are comprised of the following:

- Amortized Capital Costs of Emplacement Concept,
- Amortized Capital Costs of Port Facilities,
- Operating Personnel,
- Fuel,
- Lube Oil,
- Consumables,
- Maintenance Spares, and
- Other Annual Costs.

These costs include the amortized capital costs over an eight year amortization schedule and the normal marine system operating costs. Details of these costs are included in Section 3.2 of the Economic Viability Report. Again, the ROV Glider is included below in Table 5.2-1 as an example of Annual Cost format used in this analysis.

Table 5.2-1 ROV Glider Annual Costs

Concept: ROV GLIDER - ANNUAL COSTS				
Category	Quantity (R = ROV, L = Launcher)	ROV (Millions $)	Launcher (Millions $)	Total/Yr (Millions $)
1. Amortization Cost (8 year at 7.25%, 1994$) Full Scale Operations (Open Ocean Vessels)	R = $43.12M X $165097/M L = $43.56M X $165097/M	7.12	7.19	14.31
2. Operating Personnel Port/Dockside (6 people ea 8 hr shift, 24 hr/day, 365 day/yr @ $45.00/hr)	n/a (ref port facilities)	0.00	0.00	0.00
Open Ocean Vessels (9 people ea 12 hr shift, 24 hr/day, 365 day/yr @ $55.00/hr)	n/a (ref tug)	0.00	0.00	0.00
3. Diesel Fuel	n/a (ref tug)	0.00	0.00	(included w/tug)
4. Lube Oil	n/a (ref tug)	0.00	0.00	(included w/tug)
5. Consumables Stores	n/a (ref tug)	0.00	0.00	(included w/tug)
Geotextile Bags (166 cubic yard capacity)	13,923 bags/year $564.00/Bag	7.85	0.00	7.85
Transponders	182 transponders/year $500.00/transponder	0.09	0.00	0.09
6. Maintenance/Spares	est 3% of #1	0.21	0.22	0.43
7. Other Docking Fees	1000ft X $1.00/ft/day	0.00	0.37	0.37
Insurance (Port)	Port = .5% Capital	0.22	0.22	0.44
Insurance (Sea)	Sea = 1.5% Capital	0.65	0.65	1.30
	Total Annual Cost:	16.14	8.65	24.79

5.3 DEVELOPMENT COST ESTIMATES

Prior to full scale operation of any of these APWI concepts, prototype systems would be developed and tested to quantify both technical and environmental issues. To have a complete picture of the total system cost of any concept, the development costs associated with the analysis, design, prototype build and testing must be considered.

Figure 5.3-1 illustrates the chronological flow of a project that is initially sponsored by government funding and then transitions to commercialization. As depicted in this figure, the government would be funding the effort to demonstrate technical feasibility and industry would fund the full scale design, fabrication and operation of the system.

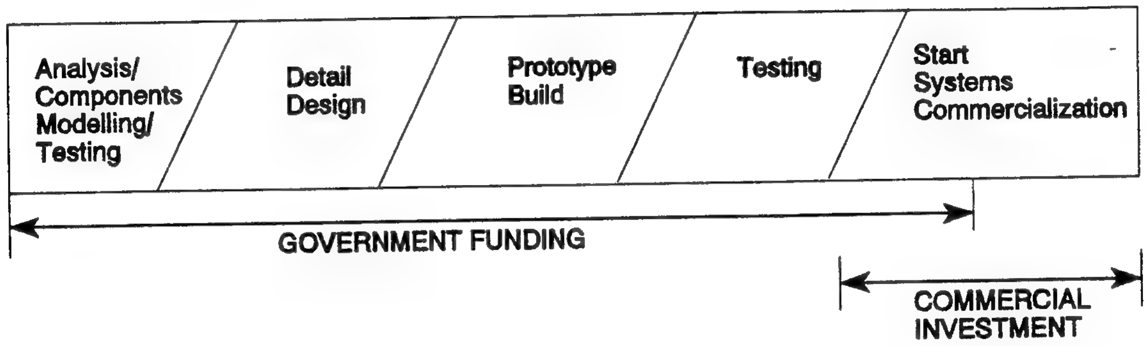

Figure 5.3-1 Chronological Flow of a Government/Industry Program

As discussed in the Technical Assessment Report for Abyssal Plains Waste Isolation Project (APWI 94-02), each concept has its own set of technical issues and risks. Shown below in Table 5.3-1 are cost estimates for each of the four APWI concepts for the various development stages.

Table 5.3-1 Technology Development Cost Estimates (In $ Million)

CONCEPT	COM-PONENT TESTING	DETAIL DESIGN	PROTO-TYPE BUILD	TESTING/ MODS	TOTAL
SURFACE EMPLACEMENT	1 - 5	N/A	N/A	N/A	1 - 5
ROV GLIDER	1 - 5	3 - 6	15-25	1 - 5	20-41
DIRECT DESCENT DISK	1 - 5	3 - 6	15-25	1 - 5	20-41
PIPE RISER	5 - 15	4 - 8	45-75	3 - 10	57-108

The rationale for the above cost figures are explained below:

■ Surface Emplacement: There are two primary technical issues to verify in order to validate this approach:

- Bag hydrodynamics modelling/testing and
- Verification that bag does not tear as it falls through the trap door.

It is anticipated that through analysis, computer modelling/simulation and component testing of bags and trap door designs, the above issues could be resolved. The cost estimate for Analysis/Component Testing is based on OTECH's experience developing and testing marine application hardware. After these issues are successfully resolved, this concept is ready for full scale design. This statement is predicated on the premise that this design is a modification of existing equipment and no intermediate scale models are necessary to verify this concept.

■ ROV Glider: The ROV Glider has several technical issues to address/resolve prior to transitioning to a commercially viable system. In summary, they are:

- Hydrodynamic characterization of the glider
- Controllability of the glider
- Reliable cargo release
- Launch and recovery of the glider

In order to resolve these issues, all facets of the development cycle would be needed. Analysis and modelling would be used to characterize hydrodynamics and control system issues. In addition, a fully functional scaled model would be required to verify the analysis results and to validate operational procedures. Therefore, detailed design of a scaled model, prototype fabrication, and functional and operational testing would be required. The associated cost estimates are again based on OTECH's experience developing and testing marine hardware.

■ Direct Descent Disk: The Direct Descent Disk concept has basically the same issues as the ROV Glider and therefore the estimated development costs fall within the same range as the Glider.

■ Pipe Riser System: The Pipe Riser has many technical and operational issues to resolve in order to verify its reliability, including:

- Catenary analysis of the pipe bundle
- Station keeping of the surface platform
- Dilution flow monitoring/control of the waste stream
- Pipe installation procedure
- Riser dynamic response
- Reliability of sea bed tractors (mobile anchors)
- Operational considerations: manned versus unmanned; at-sea maintenance; and interface with transport ship

Most of these issues can be analyzed and/or modelled as the first step in concept validation. The cost estimate for this Analysis/Modelling phase is based on relative complexity when compared to the submersible designs. Given the nature of the technical issues associated with this concept, it is assumed that a scaled physical model will not adequately validate the critical issues. For example, many of the above issues revolve around large diameter pipes installed in deep water. Performing tests of some reduced scale model in shallower water will not necessarily produce scalable results. Certainly, some operational considerations are not scalable, such as installing 600 m of pipe in shallow water is totally different from installing 6000 m of pipe in deep water. Therefore the conclusion is that a full scale, fully operational pipe riser system would have to be designed, built,

installed, and tested as the development system. The costs associated with Detailed Design and Prototype Build are then tied to the capital costs estimated for a production system as described in Section 4.7 of the Economic Viability report. The Testing cost estimate is based on relative complexity when compared to the submersible designs.

6.0 CONCLUSIONS

APWI system level requirements were derived form existing governmental regulations relevant to the waste streams, physical and chemical properties of these wastes, weather and site conditions, and vessel design constraints. Based on these system requirements, four concepts were identified that provide technically feasible solutions for implementation of contaminated dredged material, sewage sludge, and municipal incinerator fly ash isolation on the abyssal seafloor. These concepts are:

- Surface Emplacement
- ROV Glider
- Direct Descent Disk
- Pipe Riser

None of these systems exist today in the form or scale required to effectively meet the APWI requirements. All of the concepts require extrapolation of existing designs or technologies. This extrapolation process implicitly equates to risk, which can be mitigated through analyses, modelling, simulation and/or testing. In order of increasing technical risk, the concept ranking is as follows:

- Surface Emplacement
- Direct Descent Disk
- ROV Glider
- Pipe Riser

In addition to engineering feasibility, cost estimates were generated for each of the concepts. Table 6.0-1 summarizes emplacement costs per metric ton for sewage sludge and fly ash and per cubic yard for dredged material. These costs are based upon a fully utilized system with 100% operational availability. These costs form the basis for a complete systems analysis performed by Woods Hole Oceanographic Institute's economists as another task within the NRL APWI project. The resultant costs can then be compared to disposal costs for conventional methods to determine APWI economic viability.

Table 6.0-1 Emplacement Costs for APWI Concepts

APWI - SUMMARY OF ANNUAL COSTS Sewage Sludge and Fly Ash						
CONCEPT	CONCEPT ANN. COST (In Millions $)	PORT FACILITIES ANN. COST (In Millions $)	TUG ANN. COST (In Millions $)	BARGE ANN. COST (In Millions $)	TOTAL ANN. COST (In Millions $)	COST PER METRIC TON IN $ OF SEWAGE SLUDGE AND FLY ASH EMPLACED
Surface Emplacement	15.44	5.43	15.00	n/a	35.87	15
ROV Glider	24.79	5.43	14.80	n/a	45.02	20
Direct Descent Disk	32.48	5.43	14.60	n/a	52.51	24
Pipe Riser	11.38	5.43	14.56	8.23	39.60	18

APWI - SUMMARY OF COSTS Dredged Material						
CONCEPT	CONCEPT ANNUAL COST (In Millions $)	PORT FACILITIES ANN. COST (In Millions $)	TUG ANN. COST (In Millions $)	BARGE ANN. COST (In Millions $)	TOTAL ANN. COST (In Millions $)	COST PER CU YD OF DREDGED MATERIAL EMPLACED
Surface Emplacement	15.44	n/a	15.00	n/a	30.44	12
ROV Glider	24.79	n/a	14.80	n/a	39.59	16
Direct Descent Disk	32.48	n/a	14.60	n/a	47.08	20
Pipe Riser	11.38	n/a	14.56	8.23	34.17	15

From an environmental perspective, there are two approaches among these four concepts: bagged waste and loose waste. Three of the four concepts use bags to contain the waste during transit and long term isolation on the seafloor. The Pipe Riser is the only concept to deposit loose waste on the seafloor. Since the Pipe Riser has far more technical risks than the other concepts, it appears that the referred concept selection is then limited to the three bagged waste concepts. As stated above, the bagged waste concepts are basically the same from an environmental perspective. Therefore, the final concept selection can be based on technical merit.

Surface Emplacement is the preferred technical concept, based on its simplicity and its scalability from existing experiments currently being conducted by the Army Corps of Engineers. The downside of this approach is that the bags are expected to drift apart as they fall through the water column. During early experimentation to assess environmental impact of APWI, it is envisioned that bag mounds, simulating full scale operation in a localized area, would be required to be monitored over a few years. In order to accommodate this experiment, the bags would have to be deposited in a very small area. Surface emplacement is not conducive to this type of experiment.

The next most desirable technical choice is the Direct Descent Disk. It has the feature of depositing groups of bags in a very localized area. Therefore, this concept would be quite appropriate for early experiments. Its increased complexity over Surface Emplacement makes it somewhat less desirable as a long term, full scale APWI emplacement system. However, the Direct Descent Disk can also be used as a surface emplacement system. Therefore, it may be desirable to have a dual use system which can carry highly hazardous wastes to the seafloor prior to release and simply release minimally contaminated material from the surface. This approach minimizes the environmental hazard produced by a possible bag rip at the surface during release.

The ROV Glider has basically the same attributes as the Direct Descent Disk. It possesses the capability to hit a smaller target during emplacement, but also carries the associated liability of increased complexity in the control of a very large submersible, autonomous vessel. Compared to the Direct Descent Disk, its increased emplacement accuracy does not offset the increase in technical risk.

As identified in the system requirements, current top level environmental regulations would require modification to allow for the Abyssal Plains Waste Isolation of dredged material, sewage sludge, and municipal incinerator fly ash. Table 6.0-2 includes a listing of these very top level federal and international regulations that place constraints on this project.

Table 6.0-2 Top Level Environmental Regulations and Constraints on APWI

Regulation	Impact on APWI Concept	Importance
Ocean Dumping Ban Act (1988 Amendment to MPRSA)	Made it unlawful to dispose of sewage sludge in the ocean	Unless it is modified, sewage sludge can not be legally disposed of in the ocean.
Resource Conservation Recovery Act (RCRA)	Dictates testing, handling, transport and disposal practices for hazardous waste.	By law fly ash must be tested to determine if it classifies as hazardous material. If found to be hazardous, RCRA handling, packaging, transportation and disposal requirements must be followed.
London Dumping Convention, The International Convention on the Prevention of Pollution from Ships (MARPOL), and Marine Protection, Resources, and Sanctuaries Act (MPRSA)	Unlawful to dump persistent synthetics in the ocean.	May restrict the use of synthetic geotextile containers.
London Dumping Convention	Prohibited/Restricted Dumping of certain substances regarding ocean disposal.	Testing of fly ash to determine if it is hazardous may reveal the presence of one or more of these prohibited/restricted substances.